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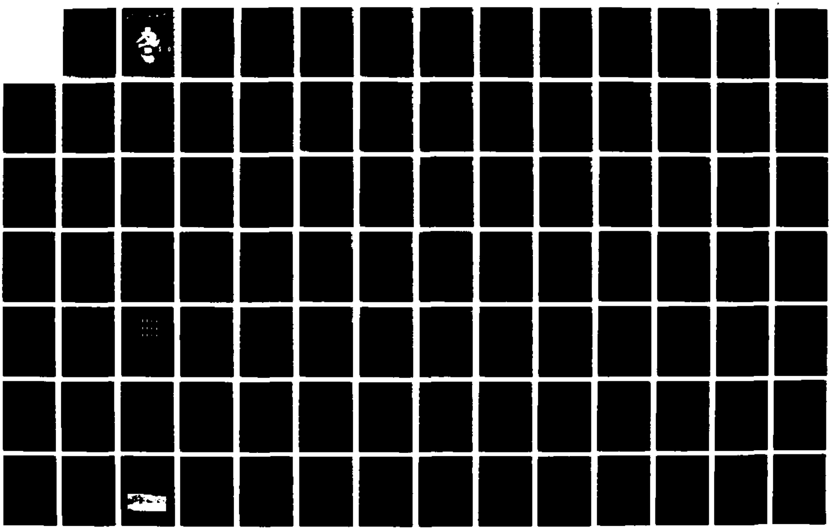

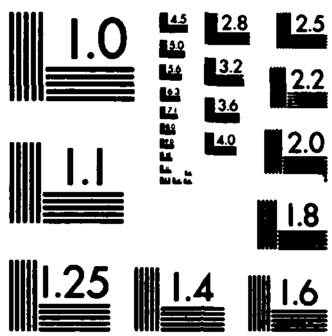

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19. ABSTRACT (Continue on reverse if necessary and identify by block number)

This is a quarterly publication presenting articles covering recent developments in Far Eastern (particularly Japanese) scientific research. It is hoped that these reports (which do not constitute part of the scientific literature) will prove to be of value to scientists by providing items of interest well in advance of the usual scientific publications. The articles are written primarily by members of the staff of ONR Far East, the Air Force Office of Scientific Research, and the Army Research Office, with certain reports also being contributed by visiting stateside scientists. Occasionally, a regional scientist will be invited to submit an article covering his own work, considered to be of special interest.

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People's Republic of China
Plasma scalpel
Plasma-enhanced deposition of diamond
Liner compression
Particle beam fusion research
High-power lasers
High-resolution imaging
Diffraction analysis
Chemical analysis
Microcracking
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Riblets
Compliant coatings
Jets
Tokamaks
Laser fusion
Heliotrons
Mirror fusion
SQUID magnetometry
Refractory materials for tunnel junctions
Millimeter and submillimeter wave detection

CONTENTS

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Cover: Katazome (stencil dyeing) is a traditional Japanese printing technique that has been used for kimono fabric and other artistic expressions for over 400 years. Since the end of World War II, however, it has become an increasingly popular method for the printing of creative designs on quality, handmade paper. This technique expresses the essence of Japanese aesthetic sense through the use of handmade washi paper, rice paste, sensitive natural colors, and the thematic material: Japanese weather. The photos on the cover of this issue of the *Bulletin* and on the rest of the issues in this volume are reproduced from the paper creations by Kichiemon Okamura, a leading Japanese print artist who has been highly praised for his moji-e (word pictures). His "Four Seasons" series has been called one of his greatest works. It features expressive renderings of the Kanji characters depicting the four seasons. This issue features "Winter."

THE 1987 JAPAN PRIZE

Sandy Kawano

Two noted agronomists, who developed superior rice strains that helped alleviate the rice cultivation crisis in starving tropical and subtropical countries, and the "father of laser technology" are the 1987 winners of the Japan Prize, Japan's equivalent of the Nobel Prize for scientific and technological achievements that advance world peace and prosperity.

On Thursday, February 12, the Science and Technology Foundation of Japan announced the winners of the 1987 Japan Prize. The Japan Prize, established in 1985 to deepen the understanding of the role played by science and technology in furthering world peace and prosperity, is grander in scope and concept than any prize currently being awarded in Japan for scientific and technological research. Dr. Henry Beachell (U.S.A.) and Dr. Gurdev S. Khush (India), whose achievements in rice breeding have stabilized rice production in tropical and subtropical nations, bringing about rice self-sufficiency in many parts of the world beset by hunger and poverty, share the award in the category for improvements of biological functions. Dr. Theodore H. Maiman (U.S.A.), the "father of laser technology," was awarded the prize in the category for electro-optics.

Dr. Henry M. Beachell, a native of Nebraska, received a Bachelor of Science degree in 1930 from the University of Nebraska, a Master of Science degree in 1933 from Kansas State University, and two Honorary Doctorate of Agriculture degrees in 1972 from Seoul National University and the University of Nebraska.

From 1931 to 1963 Dr. Beachell served as a research agronomist for the U.S. Department of Agriculture in Beaumont, TX. In 1963 he was invited to take part in the varietal improvement program by the International Rice Research Institute (IRRI) in the Philippines. His work with the IRRI (from 1963-1972) was the basis for rice breeding strategies geared to tropical and subtropical zones. In 1966 Dr. Beachell developed the IR8 strain, a superior variety that yielded high under favorable conditions. It became the basis for the "green revolution" in tropical and subtropical developing nations where rice cultivation was stagnant. The IR8 strain was not perfect, however, as there was room for improvement in the areas of quality, taste, resistance to diseases and insects, and adaptability to adverse soil conditions. After leaving the IRRI, Dr. Beachell went to work for the International Rice Research Project, in Indonesia, as a plant breeder (1972-1982). From 1982 he has been a plant breeder and consultant for the Farm of Texas Company, Texas.

Dr. Beachell has received numerous awards and honors, including the International Agronomy Award in 1983. He is a Fellow of the American Society of Agronomy and an Honorary Fellow of the Crop Science Society of the Philippines.

Dr. Gurdev S. Khush, who shares the 1987 Japan Prize in the category for improvements of biological functions with Dr. Beachell, is a native of India. He received a Bachelor of

Science degree in 1955 from Punjab Agricultural University and a Doctorate in 1960 from the University of California, Davis.

From 1957 to 1967 he was a research assistant at the University of California, Davis, and from 1960 to 1967 he also served as an assistant geneticist. In 1967 he joined the International Rice Research Institute as a plant breeder, and in 1972 he succeeded Dr. Beachell as head of the IRRI.

Dr. Khush continued Dr. Beachell's research to develop plants resistant to insects, diseases, and stresses caused by adverse soil. In 1976, after exhaustive screening of rice genetic resources, Dr. Khush successfully crossbred 13 parent genes collected from grains in 6 different countries to develop the IR36 strain. The IR36 strain, which matures early and yields high, excels in resistance against diseases and insects and is highly adaptable to various adverse soil conditions.

In 1977 Dr. Khush received the Borlaug Award for Achievements in Plant Breeding. Dr. Khush belongs to a number of professional societies, including the Genetic Society of America and the Botanical Society of America. He is a Fellow of the Indian National Science Academy and the New York Academy of Sciences.

The winner in the category for electro-optics, Dr. Theodore H. Maiman, is from California. He received a Bachelor of Science in engineering physics in 1949 from the University of Colorado, a Master of Science in electrical engineering in 1951 from Stanford University, and a Doctorate in physics in 1955, also from Stanford University.

In 1955 Dr. Maiman was appointed a section head at Hughes Research Laboratories. It was there he began his laser research. In 1960 he developed and demonstrated a ruby laser, the world's first laser. The birth of this highly monochromatic and coherent laser light source has greatly accelerated laser research, triggering the development of different lasers. In 1961 he left Hughes, and over the next 11 years he founded three corporations: Korad Corporation (1961), Maiman Associates (1968, of which he is still president), and Laser Video Corporation (1972). In 1975 he accepted a position with TRW Inc. as vice president of the Electronics and Defense Sector. In 1983 he served as director of PlessCor Optronics Inc.

Dr. Maiman is a member of many professional societies, including the National Academy of Sciences, the National Academy of Engineers, and the Institute of Electrical and Electronic Engineers. He is a Fellow of the American Physical Society, the Optical Society of America, and the Society of Photo-Optical Instrumentation Engineers.

The development of the ruby laser triggered the development of a new technology that has, over the past 25 years, made great contributions to fields as diverse as physics, medical science, and telecommunications. In recognition of Dr. Maiman's fundamental contribution through the invention of the ruby laser, he has been inducted into the National Inventors Hall of Fame. He is one of the few living Americans to join such distinguished inventors as Pasteur, the Wright brothers, and Fermi. In 1966 President Lyndon Johnson presented Dr. Maiman with the prestigious Hertz Foundation Award for his "distinguished contribution in the field of science."

This year's Japan Prize winners have taken one step further in bettering the quality of life on this planet. Dr. Beachell's and Dr. Khush's achievements in rice breeding have helped many starving tropical and subtropical rice-growing countries become self-sufficient. The laser technology developed by Dr. Maiman has been applied to medicine and has enabled surgeons to perform intricate surgeries and to enter sensitive areas of the human body, such as the eyes and the brain, with less risk.

Sandy Kawano is the editor of the Scientific Bulletin. *Before coming to Japan, she worked for the Naval Civil Engineering Laboratory, Port Hueneme, CA, as a technical writer-editor. She has a Bachelor of Arts degree in Liberal Studies from California State University, Northridge.*

THE FOURTH INTERNATIONAL WORKSHOP ON FUTURE ELECTRON DEVICES

SUPERLATTICE DEVICES

George B. Wright

The Superlattice Device Workshop was a 2-day meeting that reviewed, in 26 papers, 5 major topics: (1) epitaxial growth methods, (2) resonant tunneling devices, (3) hot electron transistors and ballistic transport, (4) high electron mobility transistors and heterojunction bipolar transistors, and (5) new heterostructure materials. The papers were heavily devoted to experiment and well represented current state-of-the-art. No qualitatively new developments were announced at the meeting.

The Fourth International Workshop on Future Electron Devices was held 9-11 February 1987 in Tokyo. It was devoted to the subject of Superlattice Devices and was primarily a Japanese meeting. Of approximately 125 attendees, about 10 were foreign and the remainder domestic scientists. The workshop was sponsored by the Research and Development Association for Future Electron Devices. In his opening remarks, Professor Kiyoshi Takahashi of Tokyo Institute of Technology, the Chairman of the Organizing Committee, reminded us that semiconductor devices could be characterized by three "generations": the discrete transistor devices, the integrated circuits, and now the quantum-effect devices. We are just experiencing the birth of this third generation, and the community is charged with excitement from the rich potential offered by the new technologies for new inventions and new concepts. Chief among these developments making possible the new devices are the semiconductor superlattices and multilayer structures that have been brought to a high pitch of perfection over a development period spanning the last 10 years. The present workshop reviewed progress in the fabrication of superlattices and reported the latest state-of-the-art in several classes of devices based upon superlattices. My feeling was that the workshop was not a forum in which many startling new results were announced but rather an excellent review of where current art has arrived and what future problems and opportunities exist.

The 26 papers were divided into sessions on fine epitaxy, resonant tunneling devices, hot electron transistors and ballistic transport, high electron mobility transistors and heterobipolar transistors, and finally new heterostructure materials. The review of this workshop will reflect a personal view of what constituted the highlights, as modified by helpful comments made to me by other attendees.

PLENARY SESSION

Dr. V. Narayanamurti gave an inspiring plenary talk that reviewed the developments in semiconductor research which have led to the present workshop and laid out for the audience the great future importance of optical communications which, in fact, underlie and give motivation to the research being done in this field. Dr. Nayaranamurti's personal command of ultrahigh speed verbal communications was impressive and enabled him to cover a great many interesting topics in the time available. It was an authoritative and exhilarating opening for the workshop.

FINE EPITAXY – The Growth of Multilayer Semiconductor Structures

To fabricate the multilayer semiconductor structures on which the devices in this workshop are based, one starts with a substrate crystal and grows the new crystalline layers on its surface, one atomic layer at a time. Usually the new layers have the same atomic spacing, or lattice constant, as the substrate. A notable exception is the so–called strained layer super–lattices. Growth of new layers on a substrate crystalline template is called epitaxy. The new atoms to be incorporated at the surface are either transported there by a carrier gas, in the chemical vapor deposition (CVD) process, or evaporated from source ovens in high vacuum in the molecular beam epitaxy (MBE) process. A recent amalgam of the two processes is chemical beam epitaxy, where the source is a gas but the chamber is kept at relatively higher vacuum. A vacuum enables one to use analytic measurements like reflection high energy electron diffraction (RHEED) in situ to monitor the actual growth.

In CVD, it is necessary to separate the desired atoms at the surface from their carrier gas, and this can be done by pyrolysis on a heated substrate, or by external laser photolysis, which allows the substrate to be cooler. A low substrate temperature is usually desirable because it decreases undesirable diffusion of components already incorporated and because creation of some types of defects is thermally activated. New methods of growth that allow lower substrate temperatures are therefore often extolled by their inventors for this virtue.

Once the new atoms have arrived at the surface, it is usually necessary for them to move about on the surface before they find their final incorporation site. The ease, or speed, with which they do this is characterized by their surface mobility. As surface mobility is often limited by a thermally activated hopping mechanism, it increases exponentially with temperature. But surface mobility can be increased by external energy sources, such as laser beams, again allowing the substrate to remain at a lower temperature. Insufficient surface mobility during growth will result in a poor quality layer.

Professor H. Sakaki, in his review paper (paper titles and authors are listed in the Appendix), pointed out that the actual parameter of interest is the diffusion **length**, L_D, whose square is given as the product of diffusion constant times diffusion lifetime. Roughly speaking, the greater the diffusion length of atoms on the growing crystalline surface, the smoother the resulting surface will be. This is a valuable viewpoint, as it allows comparison of two methods of enhancing MBE layer growth quality. In the past, MBE growth of GaAs, for example, has taken place under what is called arsenic–stabilized conditions. A sufficient flux of arsenic is maintained that all arriving gallium atoms have a very high probability of sticking. The gallium flux is then adjusted to optimize the layer–by–layer growth of the crystal. Observations of oscillatory RHEED patterns from growing surfaces as the flux was switched on and off led to the discovery that the surface may recover a very much higher perfection if the flux is switched off for a time sufficient to allow the surface atoms to migrate and smooth the surface before growth of the next layer commences. As can be seen, this method of growth improvement, given the acronym IDEALS (Interruption of Deposition for Atomic Layer Smoothing) by Sakaki and coworkers, increases the diffusion length by increasing the diffusion lifetime.

A second method of increasing the diffusion length, developed at NTT Electrical Communication Laboratories in Tokyo, and discussed at this meeting by Y. Horikoshi, is called by them migration enhanced epitaxy (MEE). In this growth method, **both** fluxes are shut off first. Then a shot of gallium sufficient for monolayer coverage is evaporated onto the surface and allowed to migrate about. It is found that under these conditions, the gallium mobility is greatly enhanced and crystals can be grown at much lower temperatures than are ordinarily needed. A reduction from 500 to 600 °C down to 200 to 300 °C was reported. The arsenic flux is turned on when the gallium layer is well established. At this meeting, Dr. Horikoshi reported that the gallium growth appeared to be "self-healing" so that an improvement of layer quality in successive layers was observed.

A third category of improved growth processes involves those which are **self-terminating** (atomic layer epitaxy (ALE)). The original conception of this class of growth by Suntola and coworkers in Finland envisioned growth of materials of compounds of the form AB, where the A–B bond strength is much greater than either the A–A or B–B bonds. If one starts with a substrate having a B-layer uppermost, and adjusts the substrate temperature to a regime that will pyrolyze A–A and B–B bonds but not A–B bonds, it is then possible to evaporate material A until the B-surface is fully covered with A. At this point no more A will stick to the surface, and the process is **self-terminated**. The A flux is switched off and the B flux switched on until a fully covered B-surface results, and self-termination again occurs. In this manner alternate layers are deposited in what one may hope will be a near-perfect structure. I am not aware of a careful discussion of defect mechanisms for this process. For the process to work as described, it is desirable that the A–B bond be much stronger than the other two types. This condition would appear to be more easily met for II–VI compounds such as ZnSe rather than for III–V compounds such as GaAs.

Additional self-terminating processes were described at this workshop in papers by Usui from NEC and by Aoyagi et al. from RIKEN. Both of these papers presented methods that derived their self-termination from saturated chemical reactions that could be manipulated. Alluding to the on/off nature of a self-terminating process, Usui called his process **digital epitaxy**. Considering this great acronym together with others such as "wave function engineering" and "phase locked epitaxy," I believe we are seeing the rise of yet another formidable new manufacturing capability in Japan.

GAS SOURCE MOLECULAR BEAM EPITAXY

In his review paper, Dr. Morton B. Panish of AT&T Bell Laboratories discussed vacuum epitaxy of semiconductors using nonelemental sources. Prior to the introduction of the gas sources by Dr. Panish's group, MBE had used elemental sources consisting of Knudsen cell type ovens. In practice, workers were very reluctant to introduce more than a few elements into their systems for fear of contamination. The new sources were motivated by the desire to use phosphorus-based compounds, and the first phase in the development of gas-source MBE (GSMBE) was the development of As_2 and P_2 beams generated from the decomposition of AsH_3 and PH_3. Following successes with these beams, the next step was to use metal-organic sources (MOMBE), allowing the use of hydride sources for the Group III elements. Advantages of high purity and possibility of scale-up for industrial production are pointed out. With this method organometallic carriers may also be substituted for the Group V elements. The efforts of Dr. Panish's group were directed toward producing alloys in the semiconductor system $Ga_xIn_{1-x}As_yP_{1-y}$ lattice matched to InP substrates. Superlattices grown with this system were shown to achieve interfaces abrupt to about one monolayer, equivalent to what had been obtained by the much more heavily researched AlGaAs–GaAs system. With 5-Angstrom-thick quantum wells, a zero-point shift of 534 meV, the largest yet reported, was achieved. A wide variety of successful applications was reported, but perhaps the most significant result is that it is now possible to grow phosphorus-based alloys, which are so important for opto-electronic applications.

MIGRATION-ENHANCED EPITAXY

As mentioned earlier the NTT paper on migration-enhanced epitaxy describes an MBE procedure that obtains improved layer flatness by increasing the effective diffusion length of atoms newly absorbed on the surface. The key ingredient was the observation that the effective surface mobility of the Group III atoms greatly increased if the As flux was turned off during growth of GaAs or AlAs. This greater mobility allows one to grow the crystals at much lower temperature. When conventional MBE growth temperatures are used, it is necessary to have the substrate temperature as high as 500 to 600 °C, resulting in interface roughness and diffusion of the impurities necessary for device operation. These two phenomena greatly degrade the operating characteristics of devices fabricated from the layered material. With the new method, the substrate temperature was lowered to 200 °C for GaAs and 300 °C for AlGaAs, a most important achievement. The higher temperature for the latter is required because of the lower surface mobility of Al as compared to Ga. It was mentioned earlier that during the growth cycle the amount of gallium supplied when the gallium source shutter is open should be the amount required for one monolayer coverage of the surface. Of course, it is extremely difficult (impossible) to supply exactly that amount, and the question arises "what is the consequence of not matching the number of Ga atoms supplied to the number of surface sites available?" Horikoshi et al. investigated this by deliberately reducing the Ga quantity and found that their RHEED oscillation monitor showed "beat" effects, with a period proportional to the mismatch. For example, with an 80-percent supply, the beat period was 5 MEE cycles. They deduced that in an island-rich surface caused by the mismatch, the Ga atoms would fill in the lowest sea-bottoms between the islands and thus be "self-healing." Absent such a mechanism, fluctuations in the Ga supply *could be very destructive.* Horikoshi et al. demonstrated the quality of quantum wells grown at 300 °C by this method by measurements of low temperature photoluminescence peaks with half-widths as low as 5 meV.

SELF-TERMINATING LAYER GROWTH

Self-terminating growth processes are of potentially great practical importance because by their nature the perfection of the layer growth is insensitive to growth conditions and therefore correspondingly easier for large-scale manufacturing. The digital epitaxy scheme described by Usui used chloride source gases such as GaCl and $Ga(C_2H_5)_2Cl$. For example, in the growth of GaAs layers using a GaCl-AsH_3 system, starting with an arsenic layer on the substrate, GaCl gas is admitted to the system, and the Ga end of the molecules attach to the arsenic atoms of the surface, leaving Cl atoms facing outwards. The GaCl molecules attach only to the As atoms, not to other Cl atoms, so when all the available As sites are occupied by GaCl molecules, the process terminates. The GaCl gas remaining is pumped out, and AsH_3 gas is admitted. Now the As atom interacts with the GaCl by a replacement interaction, in which As substitutes for the Cl and the Cl is carried away. No reaction takes place with As atoms on the surface, so the process again terminates when all of the Cl sites have been substituted. The remaining AsH_3 and other reaction products are pumped out and the cycle started over again with a clean As surface. This process can be seen to provide atomic layer accuracy of growth control. Dr. Usui stated that one cycle occupied from 6 to 45 seconds. The method is not fast for thick layers, but monolayer control would normally be required only for thin layers.

In addition to growth of normal GaAs crystals, Usui reported the growth of structures where a layer of Se was introduced at every ninth GaAs plane by introducing H_2Se into the system. Such a structure would be almost impossible to grow by ordinary methods and opens the field for a wide new range of exotic devices. As another special feature, it was reported that selective area growth can be achieved by the use of SiO_2 masks, without edge growth or facets. In addition, sidewall growth has been shown possible by digital epitaxy on (111)A,B, (211), and (511) surfaces, as well as the (100). This result has promise for the development of three-dimensionally confined structures. It can be said of this method that much progress and promise have been demonstrated in the short time since it was first announced in 1986.

Dr. Y. Aoyagi of RIKEN discussed another growth scheme where the self-terminating mechanism is provided by stimulation with an external laser. Working with source gases of trimethyl- or triethylgallium and arsine, which are introduced alternately, with a purge in-between, the As layer growth proceeds by ordinary pyrolysis at the surface. When the Ga carrier gas is introduced, it is irradiated by an argon laser. The laser is found to selectively cause the decomposition of the carrier gas when it is adsorbed at an As site and not at a Ga site. This is just what is required for process self-termination when 100-percent Ga coverage is obtained. This is a promising new technique whose power may be demonstrated in the future when more layers have been grown and characterized.

It can be seen that methods for producing multilayer materials are still in a stage of dynamic innovation, which is very promising for superlattice devices. Presently available superlattices are already adequate for many superior types of devices, so future improvements only extend the range of what is possible.

RESONANT TUNNELING DEVICES

The square potential energy barrier at the interface between two semiconductors (heterojunctions) allows one to construct potential wells in which the energy levels are quantized because the electrons are spatially confined to the potential well. It is exactly this spatial confinement of the electron in three dimensions that causes the energy levels of a hydrogen atom to be quantized to discrete levels in an analogous manner. The energy level spacing varies inversely as the square of the width of the well. At the heterojunction, the electron wavefunction tunnels from the quantum well into the barrier region, while decreasing in amplitude at an exponential rate proportional to the height of the barrier.

If by suitable choice of successive semiconductor layers one constructs two potential barriers with a quantum well in-between, the energy levels will be quantized in the well, and outside the barriers there will be a continuum of levels representing the bulk material conduction band. The conduction band will be occupied with electrons up to the Fermi level, and the quantum well width will be chosen so that the lowest level in the well is above the Fermi level in the conduction band. Such a device structure is called a double barrier quantum well (DBQW).

If the energy levels in the three regions were lined up, the electrons could use their exponential tails to tunnel through the barrier from the conduction band to the quantum well and through the second barrier into the following conduction band. This alignment can be brought about by application of an external electric field, which tilts the energy band diagram as shown in Figure 1. It is this last possibility that forms the basis for resonant tunneling devices. Simply put, if a device is constructed where the levels do not line up, initial application of an electric field causes no current to flow. As the field increases and brings the energy levels into alignment, current will begin to flow by tunneling and will reach a maximum when the levels are aligned. This is the resonance alluded to in the name of the devices. As the external field is further increased, the levels will start to go out of alignment, and the current will decrease with increasing field. In this region the device displays negative differential resistance because current decreases as field increases. This is very important because negative differential resistance can be used in circuits to build high frequency oscillators, and to build switching circuits with very high speeds. In a real-life device, the current does not fall to zero after the tunneling peak but to a minimum value called the valley. The peak-to-valley ratio of the current is taken as a measure of merit for a negative differential resistance device.

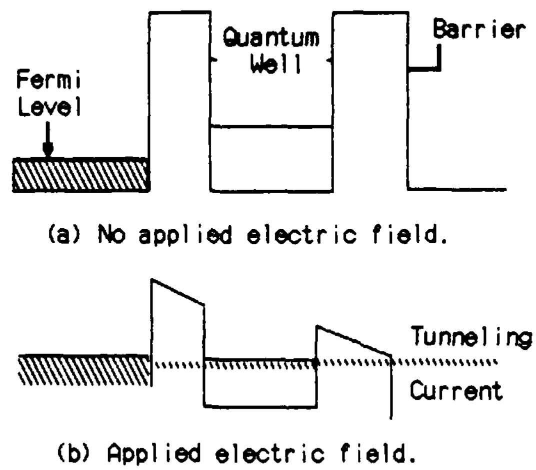


Figure 1. Double barrier quantum well.

The detailed physics of the DBQW devices is more complicated than the simple outline presented above, and at the workshop, S. Luryi of AT&T Bell Laboratories gave a lucid review discussing some of the features that are important to understanding the devices. In particular, he talked about the differences between coherent tunneling and sequential tunneling and about tunneling in superlattices, but the discussion is too complicated for presentation here. The remainder of talks in the session were reports of experimental work, which will be described next.

The paper by Tsuchiya and Sakaki presented the results of a careful series of studies designed to demonstrate the influence of device design parameters upon the performance characteristics of the devices fabricated. They first point out that the actual current through the device can usefully be separated into two components: the tunneling current and all the rest, which they term "excess current." The excess current increases superlinearly with applied voltage and will contribute to the valley current, so in general a better peak-to-valley ratio can be obtained if the operating voltage is lowered. Three major design variables can also be identified:

1. Barrier width
2. Barrier height
3. Well width

Theory shows that the resonant tunneling current is expected to have a negative exponential dependence upon the barrier width because the width at half-maximum of the transmission coefficient varies that way. Barrier height predicts a similar dependence. On the other hand, well width is a little more indirect. I mentioned that the energy levels in the well depend inversely on the square of the well width. As the width of the well is increased, the quantized energy levels drop in energy relative to the top of the barrier, so indirectly, increasing the well width is like increasing the barrier height. Note that the peak energy for tunneling also drops, which allows one to tune the operating voltage for the peak resonant current. What Tsuchiya and Sakaki reported at the workshop was a series of studies verifying these expected dependences. They showed that simple effective mass theory was a pretty good model, which could not automatically be assumed. To vary the barrier height, they used barriers composed of $Al_xGa_{1-x}As$ alloys and varied x. The maximum barrier is provided for $x = 1$ (pure AlAs). The electronic energy density of states is known for these alloys, and a very interesting conclusion of the studies was that the so-called direct, or zone-center, states dominated the tunneling, even when the indirect states in the alloy were lower in energy ($0.4 < x < 1.0$). In all of these studies, the authors took special care, for example, by interrupted growth MBE, to provide the best quality, smoothest heterojunctions possible. These careful studies provide a valuable support for future device engineering.

The paper by Ando et al. from NEC represents an interesting device innovation directly related to the ideas I have just discussed. They direct their attention to the requirements for obtaining a practical threshold voltage, V_t, for DBQW devices. Since V_t is known to be about twice the energy by which the first quantum level lies above the emitter conduction band, the threshold voltage can be reduced by increasing the width of the quantum well. But as this is done, the excited states also decrease in energy and contribute undesirable excess current. Ando et al. took another approach to lowering the threshold voltage by changing the material of the quantum well. Using GaAs for the input and output channels, and AlAs for the barrier layers, they alloyed indium into the well material while keeping the well thickness constant. When this is done, the bottom of the conduction band in InGaAs is lower than in pure GaAs, so V_t is correspondingly lowered. As In concentration was increased from 0 to 20 percent, the threshold voltage dropped from 340 to 30 mV. For measurements at 77 °K, a peak-to-valley ratio of 13 was obtained at an In concentration of 10 percent. As expected, the ratio dropped when V_t became very small.

S. Muto et al. of Fujitsu Laboratories reported devices made from another material system different from the GaAs/AlGaAs system. They fabricated DBQW devices from InGaAs with InAlAs barriers, with the alloy composition chosen to provide lattice matching to an InP substrate. Their motivation was that the lower effective mass in these alloys should provide higher peak current densities than the GaAs-based structures, and they were not disappointed. They achieved peak-to-valley ratios of 13 at 77 °K and 4 at room temperature. Their measured peak current density was 5.5×10^4 A/cm². The peak-to-valley ratio was shown to decrease approximately logarithmically with peak current density. While a great improvement of peak-to-valley current was reported over the GaAs system, the authors stated that the reasons for the improvement are not yet fully understood.

T. Nakagawa and coworkers at ETL sought to improve the device characteristics by adding an additional quantum well in a triple barrier resonant tunneling device. They made the central barrier thicker than the two outer barriers, so that it served as the principal barrier for tunneling. At 85 °K, they achieved peak-to-valley ratios of 24 but reported that models made them think that the devices had much greater possibilities than that. The full width at half maximum of the tunneling current, however, was only 30 mV, which is a great improvement over DBQW structures previously reported.

At MIT Lincoln Laboratory, T.C.L. Sollner and coworkers have been using DBQW structures to produce oscillators and mixers at millimeter and submillimeter wavelengths. In an invited talk at this meeting, Dr. Sollner described the latest achievements of their group, which include:

1. Oscillators at 56 GHz with power up to 90 μW

2. Oscillators up to 108 GHz with 1-μW power

One of the factors leading to improvement of performance was the substitution of pure AlAs barriers for the alloy barriers used in the early work. A goal of the work is to achieve oscillations at frequencies as high as 1 THz (= 1,000 GHz = 10^{12} Hertz)! The highly nonlinear form of the I-V curves has been used to make very high frequency mixers as well as oscillators. The work reported establishes the state-of-the-art as it goes and was very enthusiastically received.

HOT ELECTRON TRANSISTORS AND BALLISTIC TRANSPORT

The availability of high quality tunneling barriers has made possible a new type of transistor—the hot electron transistor, or HET. In this transistor, a thin barrier is provided between emitter and base such that when a forward voltage is provided across the barrier, electrons tunnel from emitter to base. The higher the emitter-base voltage, the higher the energy with which the electrons enter the base. High energy electrons are called "hot," hence the name HET. The collector for the HET may be formed in various ways, but one form would be a base- collector barrier thick enough to prevent tunneling but biased so that hot electrons would pass over the top of the barrier. Electrons that pass through the device without scattering are called ballistic electrons because their travel is determined at the launch site (emitter-base barrier)! These electrons contribute to the collector current. Electrons that suffer inelastic scattering most likely don't make it over the collector barrier and become part of the base current.

There are some important limitations to ballistic transport of hot electrons. In GaAs, about 0.3 eV above the conduction band minimum, there lie high density of state levels at the L-point and above this additional states at the X-point. These states put a ceiling on how hot the injected electrons can be, because as they approach 0.3 eV in energy, they begin to scatter with high probability into these higher states and are no longer ballistic. At this workshop we had papers that reviewed research on the physics of hot electron devices and papers that reported the fabrication and characterization of various types of HET.

M. Heiblum described research that he and collaborators at IBM have conducted using an HET as a "spectrometer" to study the microscopic mechanisms of hot electron transport in solids. Heiblum called his device a tunneling hot electron transfer amplifier (THETA), and its geometry, shown in Figure 2, is well described by the generic description of an HET given earlier. The IBM group has demonstrated the sensitivity of the THETA as a solid state spectrometer and clearly measured ballistic transport and the onset of intervalley scattering, with and without hydrostatic pressure. At Sony Research Center, I. Hase and coworkers, using a similar device structure, reported similar results to those obtained by the IBM group, and the findings seem to be in agreement. Explicit demonstration of the scattering gives practical impetus to the use of materials with subsidiary valleys at higher energy, and other papers at the workshop report fabrication of devices using this approach.

Two research groups (with overlapping membership) at Fujitsu presented papers at this workshop on HETs based on material systems other than n-type GaAs-AlGaAs. In the paper by Imamura et al., InGaAs/InAlGaAs lattice matched to InP substrates was used to fabricate HETs. This was done because the higher energy levels lie at about 0.55 eV, compared to 0.3 eV for GaAs. The current gain was improved to 15 for a base width of 250 Angstroms, compared to only 5 for GaAs. The authors measured a number of characteristics and concluded that they could be well represented by B.K. Ridley's diffusion theory of hot electrons. In the other paper, N. Yokoyama et al. described improvements to their earlier RHET (resonant HET) achieved by grading the composition of the AlGaAs alloy regions. They achieved a transconductance of 400 mS/mm and a maximum current gain of 5. In a second device, they retained the resonant tunneling emitter but substituted a layer of p-type GaAs for the base. The built-in field of the p-n junction sweeps carriers into the collector to improve the current gain, which now reaches values of 15 to 20. In circuits, these devices offer new functional possibilities because they exhibit negative transconductance.

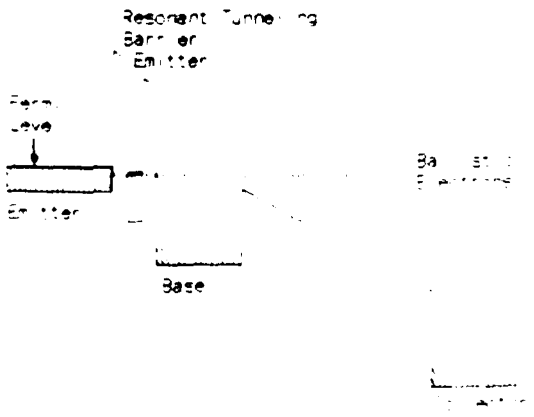


Figure 2. Tunneling hot electron transistor.

HIGH ELECTRON MOBILITY TRANSISTORS (HEMT) AND HETEROJUNCTION BIPOLAR TRANSISTORS (HBT)

The announcement of the high electron mobility transistor in 1980 by Fujitsu, followed closely by work in the U.S. and France, marked the beginning of the use of precision grown semiconductor layer structures to electronic devices other than lasers. Since its introduction, many advances in fabrication, and in understanding of the physics of operation, have been made, but by no means are all the possibilities exhausted. At this workshop, Dr. P.M. Solomon gave a very clear review of the current understanding of the physics, as well as suggestions for how design of devices may be optimized. His presentation included simple equations that may be used as a guide for thinking in design and an appreciation for the electrical requirements for the materials to be used in the devices. He pointed out that Si already possesses all of these attributes except high electron mobility, making it a very difficult material to improve on. His sketch of the various device configurations allowed us to see the bewildering variety from a unified viewpoint and allowed comparisons between different approaches. He briefly discussed the problem of electron trapping at DX centers and some of the approaches, such as superlattice elements to eliminate the impurities in the AlGaAs. In closing he presented the design for an optimized MODFET and an optimized SISFET.

A rather interesting development in HEMTs was discussed at the workshop by Dr. Fumio Hasegawa of Tsukuba University. To understand his contribution, let's look in a little more detail at the basic idea of HEMT. The original key concept, demonstrated at Bell Laboratories, was that heterojunctions could be used to provide a potential well of very pure GaAs along which electrons could propagate parallel to the interface. They could have a very high mobility because there would be no ionized impurities to scatter them. There have to be impurities somewhere in a depletion mode device, but these were located in the AlGaAs barrrier, at a distance from the channel. It was the implementation of the HEMT by Hiyamizu and coworkers at Fujitsu in 1980 which showed that this promising potential could be harnessed in a real device.

It seems that nature rarely remains simple for long. In order to improve the speed of HEMTs, it is desirable to have a short conducting channel. When the operating voltage is applied from source to drain contacts, a very high electric field results. At low fields, the velocity of the electrons is linearly proportional to the field, and the proportionality constant is the electron mobility. Hence, at low fields, high mobility means high speed. But at very high fields, the velocity versus field function is no longer linear. Instead it peaks, and then falls to a saturation velocity at high fields. This raised the question whether high mobility or high saturation velocity would be the more important quality to be sought in the channel material. In a circuit employing a HEMT, the figure of merit is the transconductance, g_m, which is the rate of change of source-drain current with gate voltage. The gate is the third electrode used to control the current.

Dr. Hasegawa analyzed device performance in terms of the inverse of the transconductance, which he called the transresistance, R_m. The transresistance is the sum of three resistances: the source resistance, R_s, which is constant; a saturation resistance, R_{sat}, linearly proportional to the ratio of (gate-channel distance/saturation velocity) = (d/v_{sat}); and an intrinsic resistance, R_{int}, which has a square root dependence on the ratio of (gate-channel distance/mobility).

$$1/g_m = R_m = R_s + R_{sat} + R_{int}$$

The transconductance is improved by making each of these terms as small as possible. Dr. Hasegawa analyzed the published data from a series of HEMTs with small d and showed that they fit his theory. Some of the devices had impurity doped channels rather than high mobility channels, yet their performance was good because of small d. An increase of mobility from 2,000 to 8,000 gave only a 20-percent increase in g_m. Hasegawa remarked that even if the mobility were infinite the transconductance would only double. In fact, this remark allows us to look at his equations and summarize the results as follows:

1. If the source resistance were zero, and the mobility infinite, the transconductance would be limited by the ratio of gate-channel distance to saturation velocity. For a given material the latter is fixed by nature and the former by the limiting current, which can be tolerated by tunneling through a thin gate barrier.

2. The source resistance is limited by current contact technology, and we see why improvements could be so valuable.

3. The channel mobility is important relative to the size of the other two resistances, and the point was made that presently this term is only 50 percent and has a square root dependence (not linear).

There is additional food for thought in these conclusions which would seem to vitiate those arguments for going to low temperature operation which are based on the observation that mobility increases markedly with a decrease in temperature. Other arguments, based on scaling, are not affected.

NEW HETEROSTRUCTURE MATERIALS

Strained-layer superlattices (SLS) were the principal topic of this session of the workshop. From the early days of epitaxy an attempt was made to match the lattice constant of the epitaxial film to that of the available substrate crystal. Failure to do so resulted in an intolerable number of misfit dislocations in the grown film. Dislocations are one method of accommodating a mismatch, while lattice strain is another. The initial atomic layers of the epitaxial film will strain to fit the substrate, but at a critical film thickness, dislocations will set in. Since superlattices are composed of very thin films, the possibility was seen to grow superlattices whose alternate layers would have negative and positive strain to accommodate to each other. At the workshop, L. Dawson gave a review of research of the group at Sandia National Laboratories, who have been among the most enthusiastic proponents of SLS. He reviewed for us the properties to be expected from SLS, and how buffer layers could be used to turn dislocations parallel to the interface to prevent their threading up through the growing crystal. The talk represented well the change from great novelty attending the original introduction of the ideas to progress in demonstrating their feasibility. Some attendees expressed the view that SLS have still to find their practical applications niche. A paper by E. Kasper of AEG discussed relevant factors in accommodating the mismatch in the SiGe system, pointing out the great dominance of the market that silicon will retain for the foreseeable future.

An experimental paper on MBE Si-Ge growth was presented by T. Sakamoto of Electrotechnical Laboratory. His group demonstrated the great power of observation of growth in-situ by oscillatory RHEED measurements. They reported that Ge-Si layers tend to grow in a three-dimensional way, resulting in a decrease of oscillation intensity of the RHEED, which was more rapid for higher Ge content. Oscillation intensity recovered, however, for subsequent growth of Si layers. There are still problems to be unravelled for this important system.

A. Ishibashi of Sony Research Center reported studies of $(AlAs)_m(GaAs)_n$ ultrathin superlattices (UTSL), where m and n ranged from 1 to 25 and layer thicknesses were about 400 nm. The materials were grown by MOCVD but shown to be of monolayer abruptness. Using Raman scattering and photoluminescence, they investigated the dimensionality of the electrons, and of the phonons, and arrived at the conclusion that as the layer thickness increased, phonons were two-dimensional until around 5 nm, after which they transitioned to three dimensions, while electrons, starting off three-dimensional, dropped to two dimensions just as the phonons were going the other way. Electrons returned to three dimensions at around 50 nm. The authors speculated on the possible changes in electron-phonon interactions in such systems.

In the final paper of the workshop, A. Ishizaka of Hitachi's Central Research Laboratory studied the growth modes of $NiSi_2$ epitaxial on Si (111) surfaces. Studying the morphology of growth, he described three substrate temperature regions. If T_m is the melting temperature of $NiSi_2$, these regimes were:

$1/4\ T_m < T < 1/2\ T_m$

Two-dimensional epitaxy

$1/2\ T_m < T < 3/4\ T_m$

Strip flow epitaxy

$3/4\ T_m < T$

Three-dimensional epitaxy

Furthermore, by considering published data on other systems, such as Si/Si, GeSi/Si, GaAs/GaAs, GaAlAs/GaAs, and InP/InP, he concluded that these regions represented a universal scaling of growth mode to melting temperature, an interesting guideline to choosing substrate temperature when starting the study of a new system

As stated in the beginning, the workshop represented a good summation of current work in the field and provided a vehicle for discussion among workers in the field of current issues. It is my impression that Japanese participation in discussions at English language meetings is becoming stronger than in the past.

George B. Wright, director of ONR/AFOSR/ARO Far East from August 1985, has been program director of solid state physics and physical electronics at ONR since 1978. He was previously Batchelor Professor of Electrical Engineering and Professor of Physics at Stevens Institute of Technology. His research interests include the relation between electronic structure and properties of solids and microscopics of materials processing for electronic devices. Dr. Wright is a Fellow of the American Physical Society and a member of the IEEE.

Appendix

WORKSHOP PROGRAM

I–1 Semiconductor Physics and the Information Age
V. Nayaranamurti, AT&T Bell Laboratories

FINE EPITAXY

II–1 Fine Epitaxy: Present State-of-the-Art in Fine Epitaxy: How good is it and how good should it be for superlattices and related devices?
Hiroyuki Sakaki, University of Tokyo

II–2 Vacuum Epitaxy of Semiconductors Using Nonelemental Sources
M. Panish, AT&T Bell Laboratories

II–3 Digital Epitaxy
Akira Usui, NEC Corporation

II–4 Switching Laser—MOVPE
Yoshinobu Aoyagi, Atsutoshi Doi, Souhachi Iwai, and Susumu Namba, RIKEN (The Institute of Physical and Chemical Research)

II–5 Migration Enhanced Epitaxy
Yoshiji Horikoshi, Nippon Telegraph and Telephone Company (NTT)

RESONANT TUNNELING DEVICES

III–1 Physics of Resonant Tunneling Devices
Serge Luryi, AT&T Bell Laboratories

III–2 Resonant Transport in AlGaAs-GaAs-AlGaAs Double Barrier Structures
Masahiro Tsuchiya and Hiroyuki Sakaki, Institute of Industrial Science, University of Tokyo

III–3 Triple Barrier Resonant Tunneling Devices
T. Nakagawa, T. Kojima, and K. Ohta, Electrotechnical Laboratory

III–4 Negative Differential Resistance of $In_{0.52}Al_{0.48}As$- $In_{0.53}Ga_{0.47}As$ Resonant Tunneling Barriers Grown by MBE
S. Muto, T. Inata, Y. Sugiyama, Y. Nakata, and S. Hiyamizu, Fujitsu Ltd.

III–5 InGaAs-Base Resonant Tunneling Devices
Y. Ando, H. Toyoshima, A. Okamoto, and T. Itoh, NEC Corporation

III–6 Microwave and Millimeter-Wave Resonant Tunneling Diodes
T.C.L.G. Sollner, Elliott R. Brown, and William D. Goodhue, Massachusetts Institute of Technology Lincoln Laboratory

III–7 Resonant Tunneling Transistors
N. Yokoyama, T. Mori, T. Futatsugi, S. Muto, T. Ohnishi, and K. Imamura, Fujitsu Ltd.

HET AND BALLISTIC TRANSPORT

IV–1 Ballistic Transport and Energy Spectroscopy of Hot Electrons in THETA Devices
M. Heiblum, IBM Corporation

IV–2 Hot Electron Transistors (HETs) Using InGaAs/InAlGaAs Heterostructures
K. Imamura, S. Muto, T. Fujii, N. Yokoyama, S. Hiyamizu, and A. Shibatomi, Fujitsu Ltd.

IV–3 Intervalley Scattering Observed in an AlGaAs/GaAs Hot Electron Transistor
I. Hase, H. Kawai, S. Imanaga, K. Kaneko, and N. Watanabe, Sony Corporation

HIGH ELECTRON MOBILITY TRANSISTORS (HEMT) AND HETEROBIPOLAR TRANSISTORS (HBT)

V–1 Device Physics and New Developments in Heterostructure FETs
P. Solomon and D.J. Frank, IBM Corporation

V–2 Recent Advances in HEMT LSI Technology
Masayuki Abe, Fujitsu Ltd.

V–3 Comments on Heterojunction FETs
Fumio Hasegawa, Tsukuba University

V–4 Monte Carlo Particle Simulation of Heterojunction FET & HBT
K. Tomizawa, Meiji University, and N. Hashizume, ETL

V–5 HBT
Tadao Ishibashi, Nippon Telegraph and Telephone Corporation

NEW HETEROSTRUCTURE MATERIALS

VI–1 MBE Growth of Strained-Layer Superlattice Device Structures
L. Ralph Dawson, Sandia National Laboratories

VI–2 InAs/GaAs Strained Layer Superlattice
Y. Matsui, H. Hayashi, K. Ono, and K. Yoshida, Research and Development Group, Sumitomo Electric Industries

VI–3 Atomic Layer Superlattice
A. Ishibashi, Y. Mori, M. Itabashi, and M. Watanabe, Sony Corporation Research Center

VI–4 Si/SiGe Strained Layer Superlattices
E. Kasper, AEG Research Center ULM, FRG

VI–5 SiGe/Si Fine Epitaxy
T. Sakamoto and K. Sakamoto, Electrotechnical Laboratory; S. Nagao, Mitsubishi Chemical Industries Research Center; G. Hashiguchi, Chuo University; and K. Kuniyoshi, Meiji University

VI–6 Growth Modes in the Heteroepitaxy of $NiSi_2$ Layers on Si
Akitoshi Ishizaka, Central Research Laboratories Hitachi Ltd.

THE INTERNATIONAL CONFERENCE ON PLASMA SCIENCE AND TECHNOLOGY, BEIJING, CHINA

A.K. Hyder and M. Kristiansen

The International Conference on Plasma Science and Technology was the first effort by the Chinese community to host an international conference on plasma science. The invited papers from foreign scientists featured technology rather than science and were more in the vein of reviews rather than innovation. The authors describe the contributed Chinese work and offer comments on present Chinese difficulties with basic research in this technical area.

INTRODUCTION

The International Conference on Plasma Science and Technology, held in Beijing, the People's Republic of China, in June 1986, was sponsored by the Chinese Society of Theoretical and Applied Mechanics and the Beijing Society of Plasma Science and Technology. About 120 papers were presented by authors from 14 different countries during the 4-day conference. Seven invited talks were given. Well over half of the papers were by authors from China, so this article will concentrate on work reported by the host country scientists. This was the first effort by the Chinese community to host an international conference in plasma science, and the effort resulted in mixed success. It was an adequate first effort and will certainly provide the basis for future meetings. There were two primary deficiencies noted: there were no significant first-report papers presented, and the attendance by non-Chinese participants did not include a meaningful number of leaders from the plasma science and technology community outside of China. This was in spite of the attempt to attract foreign participation by scheduling the meeting in tandem with the BEAMS '86 Conference in Kobe, Japan. In retrospect, the primary causes of the limited success of the conference may have been the selection of some nonactive scientists for the Steering Committee, as reflected in the quality and timeliness of the invited papers, and the lack of any significant announcement of the meeting in Western countries. In all, the conference should be viewed for what it was—an initial attempt by a fledgling Chinese plasma science community to introduce itself to the Western community and to introduce that Western community to China. The next International Conference on Plasma Science and Technology will, most certainly, be greatly improved.

SUMMARY OF THE INVITED PAPERS

The invited papers were generally not in keeping with the great attention to detail that characterized the conference overall. The opening talk by J. Kistemaker of the Netherlands was an introductory tutorial on plasma science. The second basic theory talk, given by Professor Pfender of the University of Minnesota, was a good review of heat transfer in plasma flows; unfortunately, the paper does not appear in the Proceedings even though Pfender is a member of the Steering Committee. The four remaining invited talks concerned plasma technology rather than plasma science:

1. A review of the conditions in a circuit breaker required to interrupt multi-hundred kiloampere currents and the various techniques of arc control in modern circuit breakers (Pinnekamp, Switzerland).

2. A theoretical study, which was difficult to understand, on the interaction of the arc gas flow with external and self-magnetic fields in various geometries of arc heaters, circuit breakers, etc. (Guo, China).

3. A theoretical exposition on the generation of electric arcs and the behavior of those arcs interacting with walls, in laminar flow, and under the influence of large heat fluxes (Zhukov, the author, did not present the paper; it was presented by Solineko, U.S.S.R.).

4. An historical summary of the progress of plasma technology research in China over the past 20+ years (Wu, China).

Nothing new of significance was presented in any of the invited papers. From a personal point of view, the last paper, the historical summary, was the most informative. It detailed a slow but persevering trail of progress, primarily in finding innovative applications of plasmas in industrial settings.

SUMMARY OF THE CONTRIBUTED PROGRAM

The structure of the contributed program followed the traditional Chinese classification of plasma research: plasmas with temperatures below 10^5 °K are classed as low-temperature plasmas. These are further divided into "thermal" plasmas (near local thermodynamic equilibrium (LTE)) and "cold" plasmas (nonequilibrium). The overall program was divided into these two sections, which will now be briefly reviewed.

Thermal Plasmas

Papers on thermal plasmas were presented under six different categories: basic processes and modeling, diagnostics, systems, melting and evaporation, metallurgy, and chemical synthesis and pyrolysis. The modeling studies have led to more efficient plasma generators for industry and in longer life electrode designs in high-power devices. Modeling has also been successful in describing high-frequency, plasma-assisted chemical vapor deposition reactors used for making ultrafine Si_3N_4 powders. The diagnostics work has copied Western innovations with no significant modification or improvement. Much work has been done and reported on plasma production of refractory, ultrafine, ultrahard, and ultrapure materials, with TiO_2, fine (<0.1 μm) tungsten powders, and SnO_2 as favorite examples. Applications in aerospace engineering in China have been widespread, especially in the modification of surfaces for use in hostile environments (turbine blades, heat shields, etc.). The Chinese continue to be active in coal-fired magnetohydrodynamic (MHD) power generation and continue to support work in the aerodynamics and electrodynamics of MHD channel design.

Cold Plasmas

Work on polymerization in low-pressure plasmas has been extensive. This includes such innovative applications as treating polyester fibers to improve moisture absorbance and treating cashmere wools to improve washing characteristics. Results were presented on the treatment of oil hydrogenation catalysts with hydrogen plasmas; after treatment, the activity of the catalyst was greatly improved and the loss of metal was reduced. Work was also reported on the deposition of insulating, moistureproof, and corrosion-resistant coatings onto metals, glasses, semiconductors, and actual transistor parts. From all of this, it is clear that, while the Chinese may not be very innovative in the basic sciences, they are quite capable and active in taking a technology and applying it in industrial settings. The deficiency in basic sciences is traceable in large part to the lack of sophisticated laboratory equipment--a situation that they recognize and have set about to remedy.

OTHER AREAS OF INTEREST

There were two areas reported at the conference that call for special comment. The first is rather mundane--the plasma scalpel. An argon/helium jet, less than 1 mm in diameter and operating at about 3,000 °C, has been developed to the clinical stage. It has been used hundreds of times and its special effectiveness in coagulating blood has made it an instrument of choice in procedures such as liver resections. This is noteworthy because it demonstrates the breadth of applications that are under study by the Chinese.

The second area is of enormous potential--work on plasma-enhanced deposition of diamond onto various materials, silicon being a choice. The subject was widely discussed by the participants even though there was no formal paper presented on the subject. Diamond and diamondlike coatings will revolutionize the semiconductor industry among others. The combination of high dielectric strength and high thermal conductivity make diamonds a unique material for multilayer semiconductors.

INSTITUTE VISITS

Visits were made to two institutes of the Chinese Academy of Science: the Institute of Electrical Engineering and the Institute of High Energy Physics. Much excellent work was seen at both of the institutes even though their character differed greatly. The Institute of Electrical Engineering has many efforts underway, ranging from the design of switches for specific applications (e.g., kicker switches for beam colliders, switches for an eximer laser) to rather unique and ingenious applications of pulse power technologies such as oil exploration trawlers and devices to crush kidney stones in humans. While the facilities and equipment are not modern, the innovativeness of the researchers is beyond question.

While also quite innovative, the research at the Institute of High Energy Physics has an entirely different character. This is a modern facility by any standards, with the accelerator technology duplicating that found at the Stanford Linear Accelerator (SLAC). The accelerator components, including accelerator tubes, klystrons, magnets, power supplies, capacitors, control systems, etc., are all manufactured in China. The technology capability that this represents is far above that which we normally attribute to Chinese science and engineering. While the projected beam-availability date is still many months away, there are clear indications that the technology base for duplicating the SLAC is well in hand.

Dr. Anthony K. Hyder is the Associate Vice President for Research at Auburn University. In addition, he is an Associate Professor of Physics and serves as the Director of the Center for Advanced Technology at Auburn University. Before joining the University, Dr. Hyder was program manager (particle beams, pulsed power, and space power) in the Air Force Office of Scientific Research in Washington, DC. During that period, he also served as Scientific Advisor to the Director of Research in the Office of the Secretary of Defense (Research and Advanced Technology) in Washington. Dr. Hyder, who has more than 25 years of experience as a research scientist and research administrator, holds a Bachelor of Science degree (physics) from the University of Notre Dame and a Master of Science degree and Ph.D. degree in physics and aerospace engineering from the Air Force Institute of Technology. Past positions held by Dr. Hyder include staff scientist at the Aerospace Research Laboratories and associate professor of physics and director of research at the U.S. Air Force Academy. Dr. Hyder is the author of over 45 scientific papers.

THE SIXTH INTERNATIONAL CONFERENCE ON HIGH-POWER PARTICLE BEAMS, BEAMS '86

M. Kristiansen and A.K. Hyder

This article briefly summarizes some of the highlights of the BEAMS '86 Conference held in Kobe, Japan, and discusses some of the interesting research developments at several Japanese university and industrial laboratories. Japanese institutes are conducting a wide range of beam activities, mostly related to high-power lasers. A description of some of these research efforts is provided. A paper on particle beam fusion research in China is also summarized.

The BEAMS '86 Conference was held in Kobe, Japan, on 8-12 June 1986 and was attended by some 250 scientists and engineers from 14 different countries. The second largest group of participants (after Japan) came from the U.S., with about 75 participants representing industry, national laboratories, and universities. Previous BEAMS conferences were held in Albuquerque, Ithaca, Novosibirsk, Palaiseau, and San Francisco. Professor C. Yamanaka from Osaka University and his colleagues and staff should take considerable pride in the smooth and efficient organization of the conference and the usual perfect Japanese hospitality.

The main theme of this series of conferences is the generation, propagation, and target interactions of high-power laser, electron, and ion beams. Much of the work in this area borders on classified topics, and it is always very interesting to see what the U.S. and U.S.S.R. representatives are willing to "unveil" at these conferences.

Much interest was shown in the latest reported results from Angara-5 and SNOP machines in the U.S.S.R. and the PBFA-II in the U.S. Academician Mesyats reported on liner compression experiments on the SNOP machines, on microwave generation with relativistic electron beams, and on an experiment with microsecond current-buildup, plasma erosion opening switches. Similarly, long current-buildup times in plasma erosion switches have apparently also recently been obtained at the Naval Research Laboratory in the U.S. The use of a Marx generator and a vacuum line for inductive energy storage obviates the need for the traditional Blumlein generator and is apparently the general design philosophy for the latest SNOP machine at the Institute for High Current Electronics in Tomsk.

A paper by L.I. Rudakov from Kurchatov Institute describing the use of the Angara 5-01 module for liner compression was extensively discussed after the presentation. An unusual transformer arrangement was used to match the Blumlein generator to the load, and several of the conference participants were trying to understand the geometrical arrangement. Many questions regarding the larger Angara-5 system (six or eight modules) went largely unanswered; apparently, linear experiments on this device are planned in the near future. Pinch currents of 5 MA are then expected, as compared to 1 to 2 MA on Angara 5-01.

A paper summarizing particle beam fusion research at the Institute of Atomic Energy, Beijing, People's Republic of China, was presented by Wang Naiyan et al. An 80-GW electron beam facility with a 1-MeV, 70-ns, 80-kA beam has been built. Research on electron beam diode pinching and focusing is underway. The diagnostics include N_2 laser shadowgraphy.

Beam-target interaction research includes CH_2, $C_9H_8O_5$, Al, Cu, Mo, and Au foil targets with thicknesses from 7 to 70 microns and focal spot sizes of 3 to 7 mm^2. This work is supported by theoretical calculations. Electron beam transport in drift tubes with 0.1 to 20 Torr of H_2 and 0.1 to 15 Torr of N_2 has been investigated. The drift tubes are 160 cm long with an inside diameter of 10 cm. A Monte Carlo code is used for calculating charge naturalization processes. The code includes electron impact ionization, electron avalanches, ion impact ionization, ion avalanches, charge exchange, and secondary electron escape mechanisms. An electron-beam-pumped KrF laser with a 13-J, 70-ns laser pulse has also been developed and investigated.

The host country, Japan, was of course heavily represented at the conference, and it was somewhat surprising to see the wide range of beam activities reported from a wide range of Japanese institutes. Most of it was related to high-power lasers, and the results from the Institute for Laser Engineering (ILE) at Osaka University (to which there was also a field trip) were, of course, quite evident both in size and quality. Some of the work at ILE was described by Rose and Kristiansen (1985).* ILE is a national laser fusion center that compares favorably with, for instance, the laser fusion program at Lawrence Livermore National Laboratory in the U.S. Another center of excellence in beam research is the Technological University of Nagaoka, where the emphasis is on particle beams. A post-conference conference on inertial confinement fusion by particle beams was held at Nagaoka on 16-18 June 1986.

Among the many interesting Japanese papers at the BEAMS '86 conference were those by M. Sato, T. Tazima, and H. Yonezu from the Institute of Plasma Physics at Nagoya University. They described several novel diode arrangements for pellet compression. Of interest to us was a paper by T. Shintomi and M. Masuda from the National Laboratory for High Energy Physics in Ibaraki titled "Pulsed Superconducting Magnetic Energy Storage for Pulse Loads." They summarized various energy transfer methods and the results of model experiments at 200 kJ as well as the design of a 3.2-GJ storage system. For some of the pulsed systems being considered in the U.S. and other countries, large energy storage facilities are becoming a critical issue.

We also had the opportunity to visit several Japanese university and industrial laboratories. During a visit to Nagoya University, it was interesting to see the somewhat tentative position taken by many of the researchers in the Institute of Plasma Physics. It was clear that substantial changes were planned soon after the 11th International Conference on Plasma Physics and Controlled Nuclear Fusion Research, which was held in Kyoto on 13-20 November 1986. The details of the planned changes were not available, but all signs pointed towards the design and construction of a heliotron type device. In the meanwhile, things seemed to be on "hold" until after the Kobe conference. The Plasma Physics Institute at Nagoya is one of the premier plasma physics research centers in the world and has had a very wide range of experimental efforts. Among their efforts are tokamaks, mirrors, RF confinement, bumpy torus, relativistic particle beams, toroidal pinches, and various engineering system

*Rose, M.F., and M. Kristiansen. 1985. Electromagnetic mass drivers. *Scientific Bulletin* 10, no. 1:129-132.

studies. It will be very interesting to see how the expected "reprogramming" will affect the quality of work at this well-known research institute.

Among the most interesting developments at Nagoya University was the plasma processing research by Johshin Uramoto in the Institute of Plasma Physics and by H. Sugai in the Department of Electrical Engineering. Dr. Uramoto has developed a promising ion planting technique based on a unique plasma source that is now used by several Japanese companies. Dr. Sugai is using a steady state, toroidal plasma device to create the plasmas used in semiconductor processing. This method is very promising for producing improved surfaces.

A short visit to Chubu University, near Nagoya, proved very interesting as a contrast between the "Imperial Universities" and a small private university. The university is beautifully located on a wooded hill overlooking the Nohbi Plain. The buildings and facilities are modern and attractive looking. The total enrollment is over 4,000 students. The research facilities are quite modest but some interesting work on discharge physics was explained by Professor Susumu Takeda (retired from Nagoya University).

One of the most impressive university research centers we visited was the Institute for Solid State Physics at the University of Tokyo. The Institute, which is located near the Roppongi and Nogizaka stations in Tokyo, has numerous (about eight) well-equipped divisions. We visited the Ultra-High Magnetic Field and the Laser Physics Divisions. The magnetic field laboratory is clearly one of the premier laboratories in the world. It has very impressive facilities for generating ultra-high magnetic fields from electrical energy sources (as opposed to explosive flux compressors). This includes 1.5- and 5-MJ "slow" capacitor banks and a 100-kJ "fast" bank. The magnetic fields of interest are 100 to 1000 Tesla. The facilities include several "blast protection" chambers for confining the debris that often results from such experiments.

The Laser Division also has some extremely impressive facilities including a terawatt solid-state laser system; a tunable picosecond system; and a high-power, picosecond, rare-gas halide laser system. This work is aimed at basic laser physics and development, laser spectroscopy of a wide range of materials, and short-pulse (femtosecond) generation.

A highlight of our trip was the visit to the Toshiba Hamakawasaki Works. This center for research, development, and manufacturing of high-voltage and high-current equipment is truly impressive. After having recently visited "similar" laboratories in the U.S., the quality, activities, esprit de corps, etc. of this place are striking in contrast. Our host, Dr. S. Yanabu, was extremely helpful and courteous and showed us a wide range of experiments, products, assembly procedures, etc.

This laboratory is one of the principal high-voltage, high-current testing laboratories in the world. The manufactured products are sold to some 50 foreign countries. The products cover power transmission and substation equipment and include transformers (up to 800 kV), switchgear (especially SF_6 insulated), surge arresters, etc. The assembly lines, dust-proof rooms, test facilities, etc. were of the highest quality. This is an area where the U.S. has essentially given up efforts to compete on the world market, and it is quite disturbing to realize that we are becoming essentially totally dependent on this critical technology from Japan and Europe. The only testing laboratories of similar quality in North America are those of the High Voltage Laboratory at IREQ (Hydro–Quebec) in Canada.

Toshiba's work in high magnetic field generation and gas laser development was also quite interesting. The work on high–power semiconductors was discussed briefly; the light-triggered thyristor and the gate turn–off thyristor were of particular interest. These devices have numerous potential applications and the work should be carefully followed.

Our main host and organizer for the visit to Japan was Dr. Tomoo Fujioka of the Industrial Research Institute of Japan. This new institute has very ambitious plans, primarily in the area of laser development. Dr. Fujioka arranged for one of us to give an seminar to Japanese industry representatives. Dr. Fujioka was the perfect host and organizer of a very successful and interesting visit.

Magne Kristiansen was born in Elverum, Norway, and received his Bachelor of Science in Electrical Engineering degree and his Ph.D. degree from the University of Texas at Austin in 1961 and 1967, respectively. He is currently P.W. Horn Professor of Electrical Engineering/Physics at Texas Tech University, Lubbock, TX. Dr. Kristiansen is a Fellow of the Institute of Electrical and Electronic Engineers and the American Physical Society. His current research interests lie in plasma dynamics, pulsed power technology, and quantum electronics.

BEIJING SYMPOSIUM ON ELECTRON MICROSCOPY, BSEM '86

Nancy J. Tighe

This article presents highlights of the Beijing Symposium on Electron Microscopy, BSEM '86. China has started modernizing many electron microscopy laboratories, and Chinese participation in recent international conferences, symposia, seminars, visits, and collaborative research projects has helped to upgrade electron microscopy research in China. The papers presented during the symposium demonstrate Chinese research in high-resolution imaging, electron crystallography, and chemical analysis. Session topics included quasicrystals, semiconductors, metals, ceramics, amorphous materials, and instrumentation.

INTRODUCTION

The Beijing Symposium on Electron Microscopy, BSEM '86, was held at the Xi Sanqi Hotel, in suburban Beijing, People's Republic of China, 9-13 September 1986. The symposium was the second international meeting of the Chinese Electron Microscopy Society. The first meeting was held in 1980 to mark the formation of the society. At this meeting 125 extended abstracts of papers were available for registrants, with 61 in the Materials Science Applications section and 64 in the Biological Science Applications section. Over 200 persons including guests were registered with 132 attending the sessions, 68 from abroad and 64 from China (32 of those preregistered did not attend). Electron microscopy science is international in scope and is characterized by strong interactions between researchers of different disciplines who use the same instruments and techniques to solve their materials problems. During the BSEM meeting, considerable time was spent by participants in sharing ideas and accomplishments.

The Beijing Symposium on Electron Microscopy was held the week after the International Electron Microscopy Meeting in Kyoto, Japan, and many scientists from around the world were able to attend both meetings. Papers were presented by participants from China, Japan, the U.S.A., England, Belgium, the Netherlands, Australia, New Zealand, Italy, Spain, India, France, Denmark, Finland, and Russia. Many of the invited speakers had attended the first Chinese Microscopy Symposium to assist in the formation of the Chinese Electron Microscopy Society or had visited China at other times to give advice on instrumentation and procedures. Each of the invited speakers gave at least one 30-minute talk and also co-chaired sessions with a Chinese colleague. The session co-chair arrangement encouraged questions and discussions of the papers by members of the audience. The papers were presented in English, but questions and some discussions were in Chinese.

Meetings of electron microscopy societies are traditionally international because the instrumentation and imaging theories were developed in Europe, the U.K., Canada, the U.S.A., and Japan, and collaboration between laboratories continues. China is a latecomer in modernizing its electron microscopy laboratories. The new transmission electron microscopes are capable of high-resolution diffraction, imaging, and chemical analysis. The microscopes and their accessories are expensive ($0.7M for the minimum equipment) and must have many users to justify the investment. Only a few laboratories in China are equipped with the new microscopes, and many results presented during this conference were obtained with the new instruments in Beijing, Shenyang, Shanghai, and Nanjing. Most of these laboratories are associated with the Academia Sinica. Many Chinese scientists have gone to research centers abroad and have returned to set up new facilities in their own laboratories. As stated by Professor Kuo, in his introduction to the symposium, the recent international conferences, symposia, seminars, visits, and collaborative research projects have helped to upgrade electron microscopy related research in China. The papers presented during the symposium demonstrate Chinese research in high-resolution imaging, electron crystallography, and chemical analysis. Speakers discussed research on crystallographic and phase analysis problems of current interest. Most of the papers were presented by senior researchers, with a few papers presented by graduate students.

The sessions were separated into Materials Science Applications and Biological Science Applications with two invited plenary sessions and four simultaneous sessions for contributed papers. In the papers, developments and applications of techniques of high-resolution imaging, convergent beam diffraction x-ray energy-dispersive spectroscopy, and electron energy loss spectroscopy were presented. Session topics covered materials subjects of current interest: quasicrystals, semiconductors, metals, ceramics, amorphous materials, and instrumentation.

Members of the organizing committee for the meeting included:

- Guo Kexin (K.H. Kuo), Academia Sinica, Shenyang, China
- Feng Duan, Nanjing University, Nanjing, China
- Li Lin, Academia Sinica, Beijing, China
- Ko T., Beijing University of Iron and Steel Technology, Beijing, China
- Qian Linzhao, Huang Lanyou, Tseng Mipai, and Wu Zhongbi

Secretariat:

Xiang Pengju, Yao Junen
Chinese Electron Microscopy Society
P.O. Box 2724
Beijing, People's Republic of China
Tel: 284581, 285231
Telex: 210212 SACT CEMS CN

The plenary-invited speakers for the Materials Science Applications section were:

- Guo Kexin, Zhou Dashun, Hei Zukun, and Li Doxing, Laboratory of Atomic Imaging of Solids, Institute of Metal Research, Academia Sinica, Shenyang; Dong Chuang, Department of Materials Engineering, Dalian Institute of Technology, Dalian; and Guo Yongxaing, Department of Materials Science and Engineering, Jiaotung University, Shanghai, China; "The Icosahedral Quasicrystal Found Together with the C14 Laves Phase in a Rapidly Solidified Mn-Ni-Si Alloy"
- H. Hashimoto, Okayama University of Science, Okayama; and H. Endoh, Department of Applied Physics, Osaka University, Osaka, Japan; "Some Origins of Imperfect Images at High-Resolution Electron Microscopy of Crystals"

- S. Amelinckx, Rijkauniversiteit Antwerpen, Antwerpen, Belgium; "The Study of Modulated Structures and Phase Transitions by Electron Microscopy Techniques"

- B. Jouffrey, A. Claverie, J. Faure, C. Vieu, and J. Beauvillain, LOE/CNRS, Toulouse, France; "On the RHEED Ability to Characterize Ion Implantation Damage of Silicon Surfaces"

- M.J. Whelan, G.J. Hardy, and M.L. Jenkins, University of Oxford, Oxford, U.K.; "Determination of the Nature of Small Stacking Fault Tetrahedra by 2-1/2 D Electron Microscopy"

- D.B. Williams, Lehigh University, Bethlehem, Pennsylvania, U.S.A.; "The Application of Analytical Electron Microscopy to Materials"

- C.J. Humphreys, D.J. Eaglesham, Fan Rongtuan, and C.J.D. Hetherington, University of Liverpool, Liverpool, U.K.; H.L. Fraser, University of Illinois, Urbana, IL, U.S.A.; and D.M. Maher, AT&T Bell Laboratories, Murray Hill, NJ, U.S.A.; "Convergent Beam and High-Resolution Electron Microscopy of Semiconductor Epitaxial Layers"

- L. Kihlborg, M. Lundberg, M. Sundberg, and M. Fernandez, University of Stockholm, Stockholm, Sweden; "Recent Studies of Complex Oxide Systems Using High-Resolution Electron Microscopy and Supplementary Techniques"

- J. Bovin, University of Lund, Lund, Sweden; "Real Time Video Recordings of Structural Rearrangements in Small Metal Crystals"

- Li Fanghua, Institute of Physics, Beijing, China; "Application of Diffraction Analysis in High-Resolution Electron Microscopy"

Appendix A is a list of the papers presented in the Materials Science Applications sessions by Chinese participants. Appendix B is a list of the institutes represented in the Biological Science Applications sessions, which are not discussed in this article.

HIGH-RESOLUTION IMAGING

Imaging at the atomic scale is carried out readily with the modern transmission electron microscopes that have resolutions of less than 0.2 nm. Many high-voltage, high-resolution and conventional high-resolution electron microscopes are available today that can be used for atomic scale imaging experiments. These images are patterns of black and white spots that represent atom columns and holes. The experimental difficulties lie in interpreting the image contrast with respect to the crystallographic structure of the area observed. In order to define the correct atom positions, it is necessary to prepare a series of computer-calculated images and compare them with a series of actual images. The computer programs used to calculate the images for different diffraction conditions have been developed over the past 10 years or so. Some programs are available for adaptation to mainframe computers. Those who carry out successful imaging experiments calculate the appropriate images using the required crystal orientations and diffraction conditions for each material and then make the observations. These techniques require considerable experience and access to some specialists in the methodology in order to set up the appropriate parameters. Atomic level imaging experiments are carried out in most materials laboratories. Ceramics such as titanates and niobates have been studied extensively in this manner. In China only a few laboratories have the new high-resolution electron microscopes and not many scientists have had time to do much experimentation with them. Several papers at this conference included atomic level imaging experiments with icosahedral quasicrystals, semiconductors, and ion implantation that demonstrate that the appropriate skills are available now in China.

Professors Hashimoto, Amelinckx, Jouffrey, Whelan, and Humphreys discussed the uses of atomic level imaging and diffraction analysis to identify phases and structures in several different materials. These scientists have been instrumental in developing diffraction and image analysis techniques and theories for over 20 years and presented the information in understandable formats. Professor Jouffrey described various heating and sputtering experiments carried out in the high-voltage microscope and showed moving pictures of the microstructural changes. Professor Humphreys described convergent beam diffraction pattern analysis used for identifying small crystallographic areas in layer structures. In all of these papers, the application of the techniques was emphasized and the details of the experiments were carefully described.

DIFFRACTION AND CHEMICAL ANALYSIS

The current scanning transmission electron microscopes are usually equipped with accessories that permit complete chemical and structural analysis of any specimen examined. High-resolution imaging can be combined with conventional imaging as well as convergent beam diffraction analysis, micro-beam chemical analysis with energy-dispersive spectroscopy, and electron energy loss spectroscopy techniques to identify a particular phase in microdomains a few nanometers in breadth. These unique capabilities of the current transmission electron microscopes enable the user to obtain important information but require considerable time and experience to make the information useful for problem solving. The applications of chemical analysis come from those interested in quantitative type analysis, such as that obtained using microprobe instruments, and those who wish to identify the phases in a material because of effects on material properties. The chemists and the materials scientists take slightly different approaches to solving problems. The materials scientist starts with the transmission electron microscope and adds the chemical analysis, and the chemist starts with the microprobe and adds the transmission electron microscope. The diffraction and chemical analysis techniques all require specimens with thicknesses less than a few hundred nanometers. High-resolution images and electron energy loss spectra are obtained from sample areas that are less than 10 nm.

The invited speakers discussed some of these techniques in sufficient depth to provide tutorial type information. Professor Williams emphasized the use of energy-dispersive analysis and electron energy loss spectroscopy for chemical analysis. Many examples of the applications of the techniques appeared in invited and contributed papers. The chemical analysis techniques are simple to use because of the software and instrument designs that have been developed by manufacturers and some early users. There are some cautions to be taken and these were described by Professor Williams.

IN-SITU EXPERIMENTS

In-situ heating experiments that were carried out with extremely good resolution in the high-voltage electron microscopes in Grenoble were presented in several talks given by Jouffrey. The group at Grenoble is using scanning reflection microscopy to study effects of ion sputtering on surfaces heated as high as 1,200 °C. They also are carrying out experiments on liquid metal movement in an electric field. They prepared movies of these events that showed the development of peaked and smooth shapes at the periphery of droplets. These are difficult experiments that can be done in specially equipped laboratories. Other in-situ experiments that involved heating in special stages were presented. Although heating experiments have been done for 20 years or more, the ability to retain good resolution images during the experiments adds significantly to the interpretation and usefulness of the experiment.

INSTRUMENTATION

The instrumentation papers were presented by manufacturers. The design philosophy and special features were described for the new Philips CM120 analytical scanning transmission electron microscope that was introduced in mid-1985. The Philips scanning microscope was described also. Philips, J.E.O.L., and Hitachi are now selling new instruments to laboratories in China and are also providing service for the instruments. In a few papers, specimen preparation techniques using ion thinning instruments produced in Japan were discussed.

Nancy Tighe received a Bachelor of Science degree in physics and mathematics from the College of St. Teresa, Winona, MN, and a Ph.D. from the University of London, Imperial College of Metallurgy. She worked at the National Bureau of Standards (NBS) from 1951 to 1986 in the various divisions and centers associated with ceramic materials. During the past 25 years she has concentrated on measurements of high temperature properties of ceramics and ceramic-coated metals and on the use of transmission electron microscopy for microstructural analysis of various ceramic materials. Dr. Tighe received the Silver Metal from the National Bureau of Standards for work in electron microscopy. She is Chairman-elect of the Basic Science Division of the American Ceramic Society, a Fellow of the American Ceramic Society, and a member of ASM International and the Electron Microscopy Society of America. Dr. Tighe retired from NBS in 1986 and formed the Microphase Systems Corporation. With this consulting business, her research interests in high temperature properties and microstructural analysis of advanced structural ceramics are being continued.

Appendix A

PAPERS PRESENTED DURING MATERIALS SCIENCE APPLICATIONS SESSIONS BY CHINESE SCIENTISTS

AMORPHOUS MATERIALS

- "HREM Examination of the Rapidly Quenched Pd-Si-X Alloys," by Yang Linyuan, Teng Cengming, and Li Lin, Beijing Laboratory of Electron Microscopy and Graduate School, Academia Sinica, Beijing

- "A TEM Study of the Crystallized Metastable Phases of Amorphous Pd-Si Alloy," by Wu Lijun and Guo Yongxiang, Department of Materials Science and Engineering, Jiaotung University, Shanghai; and Wu Yukun and Guo Kexin (K.H. Kuo), Laboratory of Atomic Imaging of Solids, Institute of Metal Research, Academia Sinica, Shenyang, Liaoning Province

QUASICRYSTALS

- "A Systematic Investigation for Possible Configurations of Juxtaposition of Parallel Icosahedra," by Ye Hengqiang and Guo Kexin, Laboratory of Atomic Imaging of Solids, Institute of Metal Research, Academia Sinica, Shenyang, Liaoning Province

- "A New Icosahedral Quasicrystal in Rapidly Solidified $FeTi_2$," by Dong Chuang, Department of Materials Engineering, Dalian Institute of Technology, Dalian; and Hei Zukun, Wang Longbao, Song Qihong, Wu Yukun, and Guo Kexin, Laboratory of Atomic Imaging of Solids, Institute of Metal Research, Academia Sinica, Shenyang, Liaoning Province

- "Decagonal Quasicrystal and Tenfold Twins of $Al_{13}Fe_4$ in Rapidly Cooled Al-Fe Alloys," by Zou Xiaodong, Beijing Laboratory of Electron Microscopy, Academia Sinica, Beijing, and Beijing University of Iron and Steel Technology, Beijing; and Feng Guoquang, Beijing Laboratory of Electron Microscopy and Institute of Physics, Academia Sinica, Beijing

- "Description of Hexagonal Frank-Kasper Phases by a Projection Method," by Wang Zengmai, Yang Qibin, and Guo Kexin, Laboratory of Atomic Imaging of Solids, Institute of Metal Research, Academia Sinica, Shenyang, Liaoning Province

SEMICONDUCTORS

- "TEM Study on Carbon Precipitation in CZ EFG Silicon," by Feng Sunqi, Physics Department, Peking University, Beijing; J.P. Kalejs, Cornell University, U.S.A.; and D.G. Ast, Mobile Solar Energy Corp., Waltham, U.S.A.

- "Investigation of Silicon-on Insulator Structures Formed by High Dose Implantation of Nitrogen," by Fan Tiwen, Beijing Laboratory of Electron Microscopy, Academia Sinica, Beijing; Pan Shifang, Beijing University of Iron and Steel Technology, Beijing; and Shi Wamquan and Liu Shiziang, Graduate School, Academia Sinica, Beijing

- "On the Microstructure of PTC Type $BaTiO_3$ Ceramics," by Zheng Zhudan and Zong Xiangfu, Department of Materials Science and Engineering, Jiaotung University, Shanghai; Wen Shulin, Shanghai Institute of Ceramics, Academia Sinica, Shanghai; and Guo Kexin, Laboratory of Atomic Imaging of Solids, Institute of Metal Research, Academia Sinica, Shenyang, Liaoning Province

METALLURGY

- "Transmission Electron Microscopy Study of Pr-Fe-B Alloys," by Yang Dayu, Fan Hanjie, Tian Jinghau, and Li Fanghua, Beijing Laboratory of Electron Microscopy and Institute of Physics, Academia Sinica, Beijing

- "HREM Observation of Strong Metal Support Interaction in Pt/TiO_2 Catalyst," by Wang Long and Qiao Gueiwen, Laboratory of Atomic Imaging of Solids, Institute of Metal Research, Academia Sinica, Shenyang, Liaoning Province

- "A TEM Study on the Nature of Strengthening and Toughening in a Matrix Steel 65Cr4W3Mo2VNb," by Huang Guanghei, Cao Niasun, and Cui Kun, Huazhong University of Science and Technology, Wuhan, Hubei Province

- "Electron Microscope Observation of Fracture in Pure Nickel," by Li Jing, Beijing Research Institute of Materials and Technology, Beijing; and Zhang Tongyi, Chu Wuyang, and Hsiao Chimei, Beijing University of Iron and Steel Technology, Beijing

- "Using Weak Beam Technique to Study the Effects of Cobalt on the Stacking Fault of Refractoloy 26," by Ren Yunrong, Li Xiaofong, Zhuang Linzhong, and Chen Gouliang, Beijing University of Iron and Steel Technology, Beijing; and Xu Jialong, Shanghai Iron and Steel Institute, Shanghai

- "In-Situ Observation of Crack Propagation by TEM," by Dai Shujuan, Zou Hongcheng, and Zhang Yizeng, Huazhong University of Science and Technology, Wuhan, Hubei Province

- "Crack Resisting Process of Polypropylene Plate," by Zhang Guijia, Department of Chemical Engineering, Tsinghua University, Tsinghua; Pan Ziang, Department of Biomedical Engineering, China-Japan Friendship Hospital, Tsinghua; and Liu Shuwen and Yan Yunjie, Research Institute of Materials Science, Tsinghua University, Tsinghua

INORGANIC MATERIALS

- "A Study on the Defect of Carbon Fiber by SEM," by He Fu and Wang Ruene, Institute of Coal Chemistry, Academia Sinica, Taiyuan, Shanxi Province

- "A New Suboxide of Nickel (Ni80) Observed by HREM," by Lu Jun, Guan Qinfeng, Guan Runan, and Guo Kexin, Laboratory of Atomic Imaging of Solids, Institute of Metal Research, Academia Sinica, Shenyang, Liaoning Province; and H. Hashimoto, Okayama University, Japan

- "A TEM Study of the Evolution of Discommensuration in BSN," by Pan Xiaoqing and Feng Duan, Institute of Solid State Physics, Nanjing University, Nanjing, Jiangsu Province

- "HREM Study of Mo/GaAs Interfacial Structural Change After Annealing," by Zhang Shuyuan and Wu Ziqin, Structure Analysis Laboratory, University of Science and Technology of China, Hefei, Anhui Province

HIGH-RESOLUTION/PHASE ANALYSIS

- "Microstructural Characteristics of Deformed and Corroded Ceramics," by N.J. Tighe, National Bureau of Standards, U.S.A.; Sun Jing, Shanghai Institute of Ceramics, Academia Sinica, Shanghai; and Lu Yining and Hu Rongming, Shanghai Institute of Testing Technology, Shanghai

- "HREM and Electron Diffraction Study on Xiuyan Jade," by Wu Xiaojing and Li Fanghua, Graduate School, Academia Sinica, Beijing; and H. Hashimoto, Okayama University, Japan

- "A HREM Study of the Intergrowth Structures of σ and μ Phases," by Zhou Dasheng, Ye Hengqiang, and Guo Kexin, Laboratory of Atomic Imaging of Solids, Institute of Metal Research, Academia Sinica, Shenyang, Liaoning Province

CHEMICAL ANALYSIS

- "The Grain Boundary in Wrought Superalloy with Microaddition Mg," by Zhu Zing, Ma Peili, Cheng Zhiying, Zhang Shun, and Gao Liang, Central Iron and Steel Research Institute, Beijing

- "A Study of the Chemical Shifts on Different Al_2O_3 Variants by EMPA and XPS," by Chen Rongzhao and Wu Lili, Tianjin Research Institute of Chemical Industry, Tianjin

- "TEM Observation of Substructure of Al-Mn Quasicrystal," by Fan Chenggao and Wu Ziqin, Structure Analysis Laboratory, University of Science and Technology of China, Hefei, Anhui Province

- "Several Problems on Analysis of Trace Elements by EPMA," by Xue Dejum, Analyzing Testing Center of Shandong Province, Jinan, Shandong Province

- "The Dependence of X-Ray Intensity Factors of Pure Elements on Accelerating Voltage in EMPA," by Xu Li and Wu Ziqin, Structure Analysis Laboratory, University of Science and Technology of China, Hefei, Anhui Province

Appendix B

INSTITUTES REPRESENTED IN BIOLOGICAL SCIENCE APPLICATIONS SESSIONS

- Institute of Basic Medical Sciences, Department of Pathology, Department of Neurobiology, Chinese Academy of Medical Sciences, Beijing
- Institute of Medical Biology, Chinese Academy of Medical Sciences
- Experimental Animals Research Center, Chinese Academy of Medical Sciences
- Beijing Institute of Traumatology and Orthopedics, Beijing
- Department of Biology, Beijing University, Beijing
- Beijing Union Medical College, Beijing
- Electron Microscope Laboratory, Beijing Medical University
- Institute of Virology, Chinese Academy of Preventive Medical Sciences
- The First Hospital of Beijing Medical University, Beijing
- Institute of Basic Theory of TCM, China Academy of Traditional Chinese Medicine, Beijing
- Institute of Biophysics, Academia Sinica, Beijing
- Institute of Botany, Academia Sinica, Beijing, Beijing Shi
- Central Laboratory and Nan Fang Hospital of the First Medical College of P.L.A., Guangzhou, Guangdong Province
- Department of Pathology, Sun Yet-sen University of Medical Sciences, Guangzhou, Guangdong Province
- Institute for Cancer Research of Yunnan, Kunming, Yunnan Province
- Military Medical Institute, Kunming, Yunnan Province
- Shanghai Institute of Materia Medica, Chinese Academy of Sciences, Shanghai, Shanghai Shi
- Department of Biophysics, Shanghai Medical University, Shanghai
- Department of Cell Biology, China Medical University, Shenyang, Liaoning Province
- Hebei Medical College, Shijiazhuang, Hebei Province

- Department of Experimental Pathology, Institute of Hygiene and Environmental Medicine, Tianjin, Tianjin Shi
- Department of Histology and Embryology, Xinjiang Medical College, Urumqi, Xinjiang Province
- The Xinjiang Institute of Chemistry, Academia Sinica, Urumqi, Xinjiang Province
- Research Laboratory of Electron Microscopy, Huazhong Agricultural University, Wuhan, Hubei Province
- Institute of Cell Biology, Xiamen University, Xiamen, Fujian Province

REVIEW OF WORKSHOP ON DESIGN, ANALYSIS, AND RELIABILITY PREDICTION FOR CERAMICS

PART II

Edward Mark Lenoe

This article is the second part of a two-part review of the workshop on Design, Analysis, and Reliability Prediction for Ceramics. The topics covered in this part include acoustic emission source characterization, design and analysis of a silicon nitride swirl chamber, definition and measurement of fracture parameters, reliability technology, flaw size and strength distribution, reliability and lifetime prediction of ceramic components, microstructural damage in high-temperature fracture and creep, mechanical testing methods, defect formation during powder processing and sintering, advanced ceramic systems for blower fan applications, application to large-size heat exchangers, application of ceramic boards to air bearing technology, mechanical properties of glass-bonded ceramic composites, and European-sponsored research on technical ceramics.

SUMMARY

This concludes my review of the workshop held at the International House of Japan in Tokyo on 18 and 19 September 1986.* In retrospect, the meeting seems to have been quite productive, and as usual in this type of activity, many questions were raised while considering the technical details. Hopefully, answers can be obtained to some of these ponderings. By way of example of some issues of importance, many of the speakers commented that finite element stress analysis was used to design their particular component of interest. Unfortunately, this statement is usually made as if those three words totally explain the procedure and as if all finite element codes are the same! Rarely was any mention made, for instance, of the heat transfer codes or the associated thermal calculations that are an integral part of the modeling of any high-performance, high-temperature system. In a number of instances in the past, comparisons have been made of the stress estimates calculated by different organizations, each using their in-house analytical capabilities. Obviously, the nature of the numerical computation, as well as the assumed boundary conditions, such as estimated heat transfer, and other controlling boundary conditions and parameters of the system, all influence the final results obtained. So it is rare that such comparison arrives at exactly the same calculated value. Previous discussions with experienced turbine and diesel engine designers regarding their own confidence in estimated peak stresses, strains, temperatures, contact forces, coefficients of friction, heat transfer values, etc., for particularly complex parts or for new engine

*Note: In Part I (*Scientific Bulletin* 11, no. 4:35-69), the word "theological" was inadvertently substituted for "rheological"! While I pursue materials science with fervor, it has not reached the level of religion.

designs, are of interest. Several top designers have stated that the peak values could easily be underestimated by 40 to 60 percent. They mentioned that this was one reason why test cells and numerous engine "builds" or "mods" are necessary in the evolutionary development of any engine. My point is that it would be very useful for authors to routinely provide more details on the nature of the computer codes and the other controlling conditions and assumptions applied. Perhaps it would be productive for the experts to even conduct something like the equivalent to round-robin evaluations on analysis of specific important selected systems. This would serve to narrow down the areas of uncertainty and reduce the likelihood of future unanticipated failures in ceramic components.

The topic of mechanical testing received special attention during this workshop. It was surprising to hear of the scope of activity in tension testing of ceramics and to gain some insight into the magnitude of the effort in Japan. In the United States, high-temperature tension testing on cermets and rocket nozzle and heat shield materials was fairly extensive in the late 1950s and early 1960s, followed by a spate of activity on tension testing of high-performance ceramics in the early 1970s. But only recently has increased attention been devoted to such testing of ceramics in America. There are numerous inhibitors regarding tension testing, namely, expense and difficulty, the fact that many advanced ceramics are truly still in a developmental stage. So it is encouraging that new impetus is being placed on this important aspect of generating design allowables for high-performance ceramics. However, at this stage of development the magnitude and quality of the data base are not evident, and it would be useful to attempt to review this aspect.

During this meeting it was evident that there was much activity devoted to mechanical characterization of ceramics and furthermore that a wide variety of testing specimens as well as stress states had been explored. Of course, much flexural data had been accumulated, but tension, compression, and torsion tests for monotonic loadings were also reported. An impressive effort in creep, fatigue, and hot spin testing was also evident. And most importantly, significant progress has been made towards standardization of various tests. The Japanese Industrial Standard, Testing Method for Flexural Strength (Modulus of Rupture) of High-Performance Ceramics, JIS R 1601-1981, was issued a number of years ago. Now JIS R 1602-1986, Testing Methods for Elastic Modulus of High-Performance Ceramics, has been translated and is available from the Japan Standards Association, 1-24, Akasaka 4, Minato-ku, Tokyo 107, Japan. The standard concerns three- and four-point bend tests, bend resonance methods, and ultrasonic pulse methods. Meanwhile, much activity is devoted to standardization activities. Round-robin testing appears to be underway in fracture toughness testing and in numerous other methods. One can anticipate a tension standard and a fracture toughness standard within a year or two. In the fracture toughness area, the microhardness indent method is receiving a great deal of attention.

Turning now to the specific sessions, speakers in Session III, Test and Evaluation Results, presented a variety of interesting information. Professor Kishi of Tokyo University provided an excellent review of his studies of acoustic emission techniques and speculated about using the methodology for quantitative determination of microcracking in metals as well as ceramics. The potential includes early failure detection or elimination and materials characterization and selection. Aspects of materials characterization for design, as well as the design procedures themselves, were discussed by Kawamoto and Shimizu, Toyota Motor Corporation, and by Srinivasan, Seshadri, and Chia of Sohio Engineered Materials Company. Professor Nicholson provided useful insights regarding multiphase composite behavior and possibilities for materials development.

In Session IV, Advanced Reliability Methodology, speakers from NGK Spark Plug and NGK Insulators presented the spectrum of current reliability approaches, and the presentation by Tajima was particularly thorough. Professor Matsuo, Tokyo Institute of Technology, covered advanced methodology. Larker, of ASEA, described a variety of tension test techniques and discussed process and product development in some detail. Schubert et al., Max Planck Institute, discussed early experiences in discovering defect introduction in powder processing and sintering of advanced ceramics. Dr. Tighe's in-depth presentation on microstructural damage in high-temperature creep and fracture was quite thorough and was well received.

In Session V a number of industrial applications were discussed. The increased efficiencies and enhanced performance capabilities for large blower fans were reported by Kido, Hamada Blower Co. Large-size heat exchangers were described by Ueno et al., Kurosaki Refractories Co. Ceramics for air bearings, slides, and measuring instruments were discussed by Suzuki, Toto Co. Professor Wachtman, Rutgers University, reviewed the wide range of possibilities for property modification in glass-bonded ceramic composites. The session concluded with an overview presentation of European ceramic research activities by Dr. Wurm, head of Advanced Materials Research of the Commission of the European Communities. The workshop concluded with a panel summary by the various session chairmen. These summaries have been included at the end of each session. In conclusion, the workshop was successful in providing a wealth of valuable information and insight into the current status of ceramic technology.

SESSION III. TEST AND EVALUATION RESULTS

AGENDA

The following speakers discussed component and specimen test procedures, results, and interpretation. The status of quality assurance and nondestructive evaluation was briefly discussed.

- Teruo Kishi, Institute of Interdisciplinary Research, Faculty of Engineering, Tokyo University, "Evaluation of Ceramics by Acoustic Emission Source Characterization"
- Hiroshi Kawamoto and T. Shimizu, Toyota Motor Corp., Material R&D Department, "Strength Analysis of Silicon Nitride Swirl Chamber for High-Powered Turbocharged Diesel Engines"
- Peter S. Nicholson, McMasters University, Ontario, Canada, "Novel Technique of Toughening and Strengthening Brittle Materials"
- M. Srinivasan, S.G. Seshadri, and K. Chia, Sohio Engineered Materials Co., Niagara Falls, N.Y., "Characterization for Design and Performance Prediction of Ceramics"

COMMENTS

Kishi

Professor Kishi presented an excellent paper on advanced acoustic emission techniques for quantitative microcracking in metals and ceramics. In the case of alumina, microcracks were detected in front of precracks; their sizes were estimated and compared with direct measurement using scanning electron microscope observations. Kishi suggested that microcracks less than 50 microns contribute to the enhancement of fracture resistance and microcracks larger than 70 microns become the origin for unstable fracture.

An essential step to understanding the fracture mechanism in any material is evaluation of the nucleation and coalescence of microcracks, since they are ordinarily the driving source for final fracture. As part of attempts to measure and quantify this behavior, Kishi borrowed terminology from earthquake specialists. He described his advanced acoustic emission technique to obtain the source function tensor as seismic moment for microcracks. As he emphasized, meaningful parameters for understanding characteristics of microcracks are their location, inclination to the fracture plane, fracture mode, sizes, and rise time or mean nucleation rates. The paper described the theoretical background of acoustic emission characterization, as well as the hardware and software to estimate such source functions.

His characterization is based on models used not only in seismology but in dynamic fracture mechanics and dislocation theory. Kishi's relationship between source function and detected signal is based on linear response theory. Since the analytical method is valid only for infinite or semi-infinite media, Kishi developed requisite experimental methods and simulation by finite difference techniques. In particular, he developed a three-dimensional numerical simulation of elastic wave propagation, and from these results an arbitrary source position can be estimated. For instance, three-dimensional location was carried out by measuring the time difference of initial longitudinal waves between two independent transducers. In principle, the inclination of the microcrack plane may also be obtained by similar means.

The technique was applied to fracture toughness testing of alumina using a compact tension specimen and several transducers as shown in Figure 1. It was observed that microcracks nucleate at the middle of specimen thickness at the initial stage and near the specimen surface at a later stage. Waves detected by the three transducers indicated that microcracking generally consists of Mode I behavior, as the radiation pattern in Mode I always has the same phase. The radiation patterns predicted for Modes I, II, and III are shown in Figure 2.

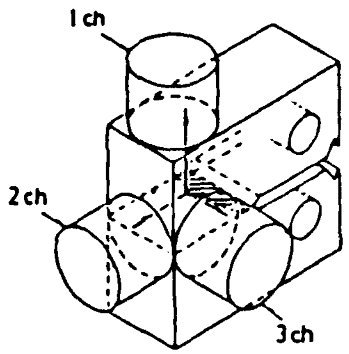
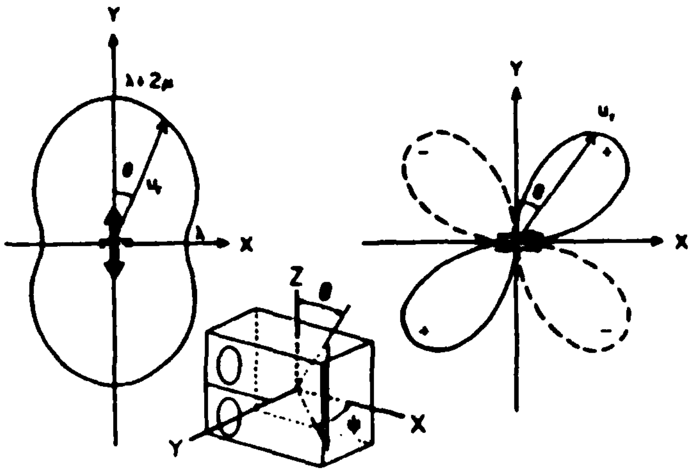


Figure 1. Compact tension specimen and transducers.



(a) Mode I tensile cracking.

(b) Modes II and III shear cracking.

Figure 2. Radiation pattern of acoustic emission signal.

Figure 3 summarizes the distribution of observed microcracks using the acoustic emission technique. The microcracks range, for the initial events, from 10 to 50 microns. At the later stage, larger cracks varying from 70 to 100 microns are observed, and these cracks then become the source of final fracture. Kishi concluded that in room-temperature fracture of alumina there are two types of fracture: (1) small microcracks that contribute to fracture resistance and (2) larger cracks directly connected to final fracture. His system appears to be suitable for conducting extensive fracture research at room temperature. It will be interesting to see whether approximate theories can be developed for inelastic and nonlinear phenomena and whether transducers and associated experimental methods can be developed for high-temperature fracture evaluation.

Question:

You mentioned citing Evans' work that the wake of the microcracking is important. In the fractograph you showed, there was a main crack that zig-zagged and you attributed the zig-zag to the microcracking, and yet I did not see any wake. Does that wake exist?

Answer:

In high toughness materials we always located the microcracks, zig-zags, and flat paths and observed them. As Professor Kobayashi suggested, there is a possibility that energy dissipation because of shear, inclination, or branching effects exists. So far we cannot treat this effect quantitatively. When I found Evans' equations I applied them. I am not sure the wake exists or is unique or not.

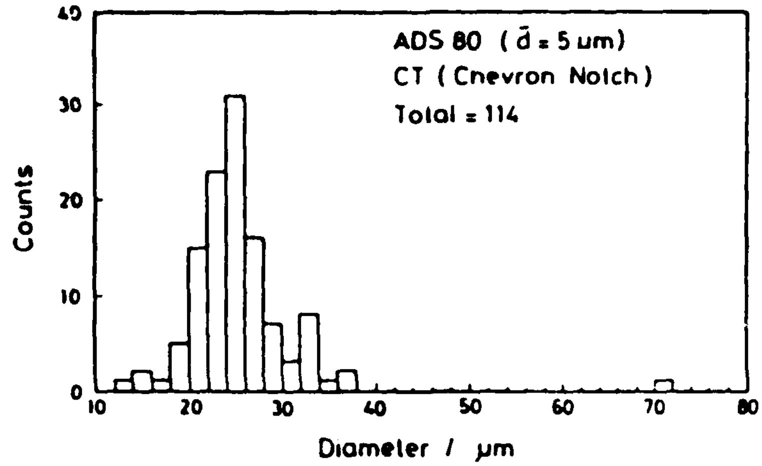


Figure 3. The distribution of crack diameter evaluated by acoustic emission source characterization.

Question:

I wonder if you would comment on two matters. One has to deal with the curvature of the crack front in a double-torsion specimen. In some materials there is quite a curvature in the crack front, so the velocity of the crack growth is quite variable from one point along the front to another. The stress intensity is also variable along the front. Isn't it difficult to interpret the crack velocities?

Answer:

In my case we make estimates. This is a result of microcracking within the materials, not on the surface. We estimate the rise time from analysis. Of course, to decide between Mode I, II, or III is very difficult! But as I showed in one of my figures, if we decide on a tensile component, all of the components of this material, neglecting the shape of the microcracking, seem to be satisfactory. So in a simple case we can decide the direction of tensile or shear cracking. I believe as far as we can detect microcracking we can reasonably estimate the velocity.

Question:

You saw the formation of microcracks ahead of the crack tip and at the same time the change in the load deflection curve. Usually fracture mechanics people put that together into the n value and say that is subcritical crack growth. What we would like to have is a combination between, or somehow the correlation between, the big n value as a continuum mechanics value and the microstructure. If this correlation were to be in microstructural terms, then true design of more durable heat-resistant ceramics would be much easier! Do you think it's possible with your method?

Answer:

As long as I can detect this signal I am sure measured response to the microstructure is kept.

Comment:

You imply or suggest there is another contribution for this nonlinear curve or load versus crack resistance–displacement curve.

Reply:

Maybe in the case of ceramics, measurements at room temperature can be useful for microstructural correlations with mechanical response.

Kawamoto

Kawamoto of Toyota Motor Corporation presented an excellent paper on the design and analysis of a silicon nitride swirl chamber for a turbocharged diesel engine. The swirl chamber was produced with sintered silicon nitride, injection molded and isostatically pressed, containing yttrium oxide additive, about 4 to 5 weight percent, and complex magnesia alumina compound, also about 4 to 5 weight percent. This material attained a density of 3.22 g/cm³. Extensive testing of mechanical properties was reported. Figure 4 shows the specimens used, which included flexure, tension, and torsion. Figure 5 shows the ring tests and curved beam tests on specimens machined from actual swirl chamber components.

Fracture behavior was investigated in several ways, including the Vicker's indentation method, chevron-notched beam, and tensile load rate testing. Furthermore, flexural stress rupture experiments were completed. Some flexural, tensile, and torsion results are summarized in Figures 6 and 7.

Some of the time-dependent and fracture properties of the silicon nitride are shown in Figures 8 through 11. These properties include fracture toughness at high temperature (Figure 8), flexural creep rupture (Figure 9), tensile rate testing (Figure 10), and crack velocity as measured using chevron-notched specimens (Figure 11). Based on state-of-the-art approaches, linear elastic fracture mechanics, and elementary Weibull theory, it is possible to estimate the associated crack velocity exponent assuming a power law for crack growth. Kawamoto reported that for the various experiments conducted, based on these simple approaches, the crack growth exponent varied from 30 to nearly 80.

Thermal stresses at the most severe operating conditions were estimated by finite element analysis. Some experimental verification of the calculated stresses was accomplished at low temperatures by means of strain gauges. The stress-strain measurements, as well as the peak thermal stress estimates, are presented in Figures 12 and 13.

It can be seen in Figure 13 that high tensile stresses are produced in the upper and lower outside of the chamber, and these stresses range from 200 to 300 MPa. Comparing these stress values to the observed strengths suggests there is little if any possibility of short-time failure from the strength viewpoint. Toyota prepared an applied-stress—versus—failure—time diagram based on nominal fracture parameters and linear fracture mechanics. The diagram, shown in Figure 14, was used for lifetime predictions. For example, if a proof-to-applied-stress ratio of 1.5 is used, for operating stresses of 200 to 300 MPa, the minimum lifetime is at least 3 years. Furthermore, to investigate possible strength degradation, ring and circular segment beam specimens were taken from chambers subjected to long-term exposure durability tests. According to the results shown in Figure 15, no significant strength degradation occurred for the period of observation. Therefore, it was believed that the chamber had sufficiently good properties for the application.

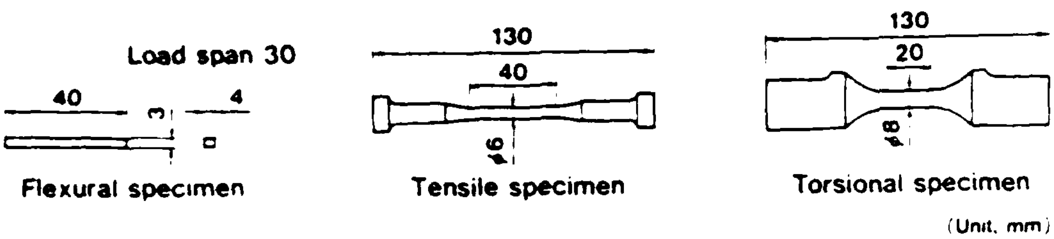


Figure 4. Specimen configuration.

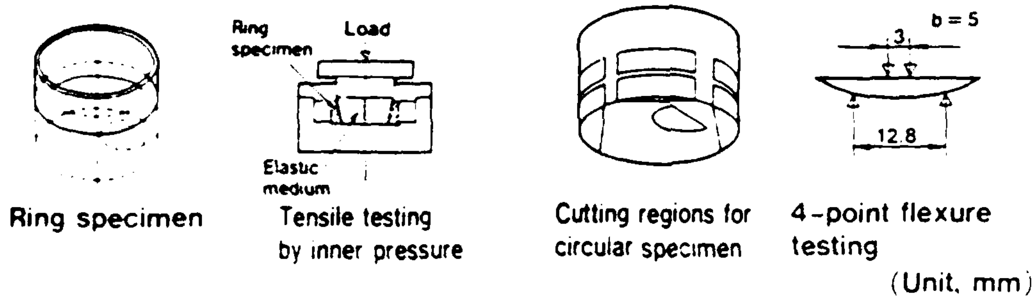


Figure 5. Testing methods.

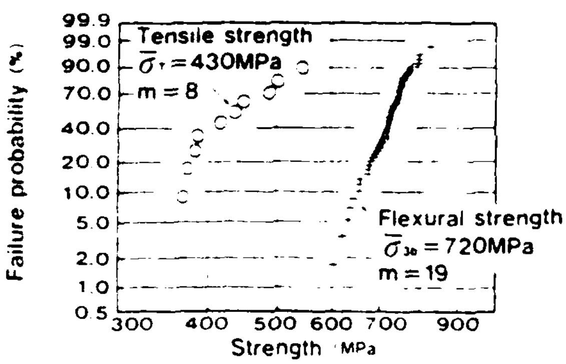


Figure 6. Strength distribution versus failure probability at room temperature.

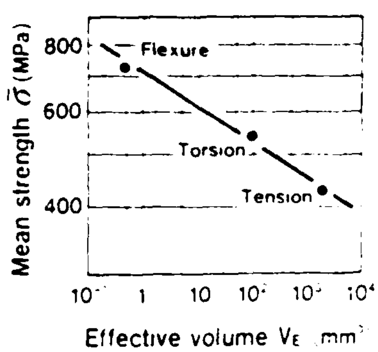


Figure 7. Mean strength versus effective volume.

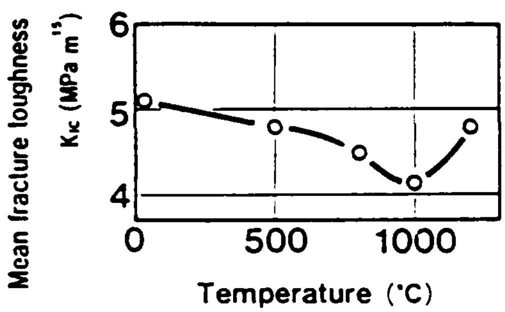


Figure 8. Fracture toughness at high temperature.

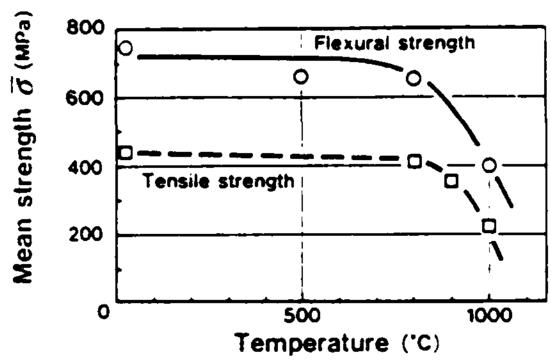


Figure 9. Flexural and tensile strengths.

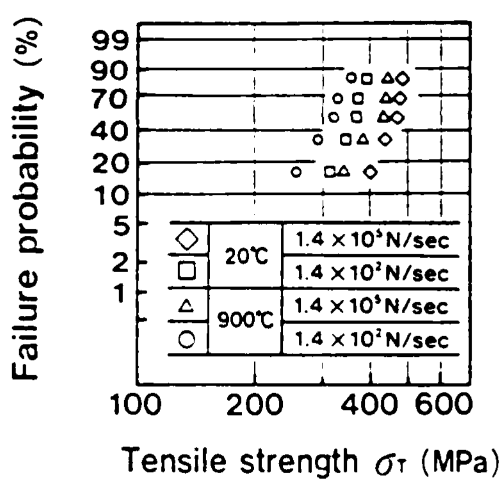


Figure 10. Dependence of tensile strength on load rate.

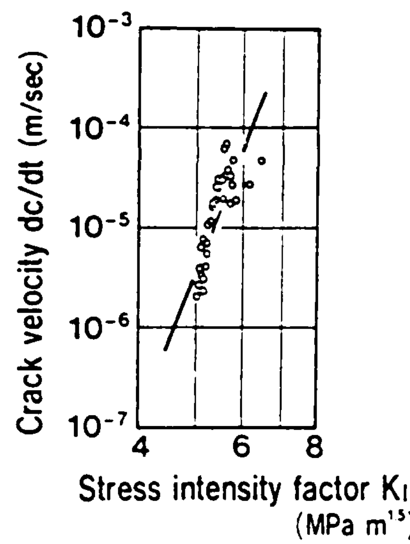


Figure 11. Crack velocity-stress intensity factor diagram.

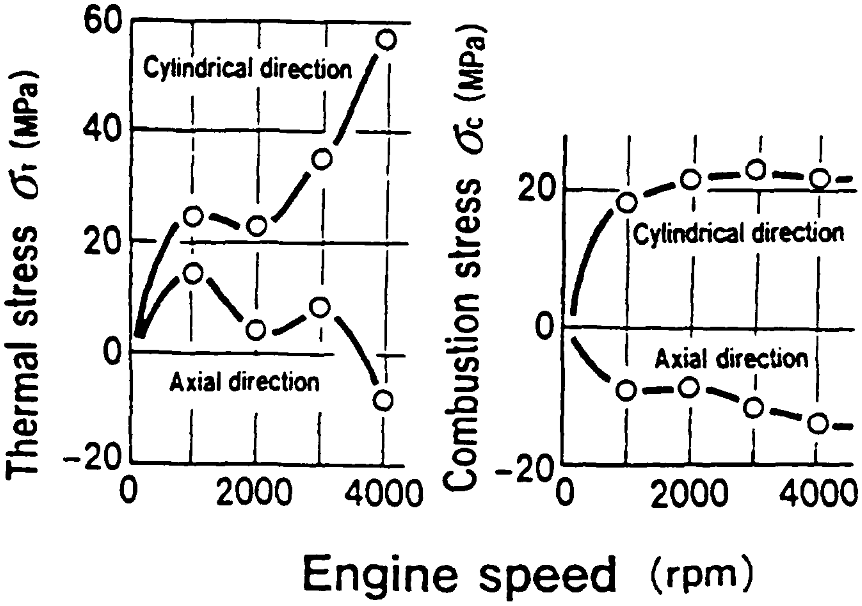


Figure 12. Measured service stresses applied to swirl chamber.

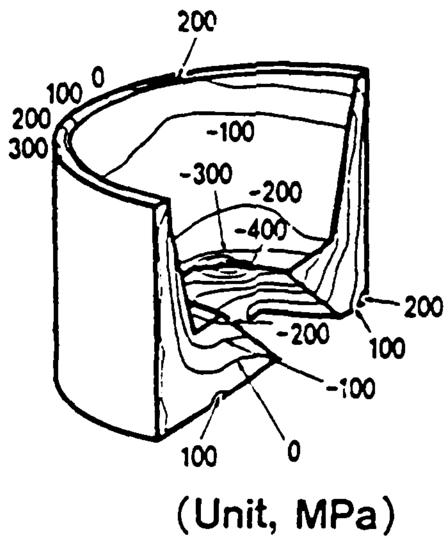


Figure 13. Finite element method thermal stress distribution.

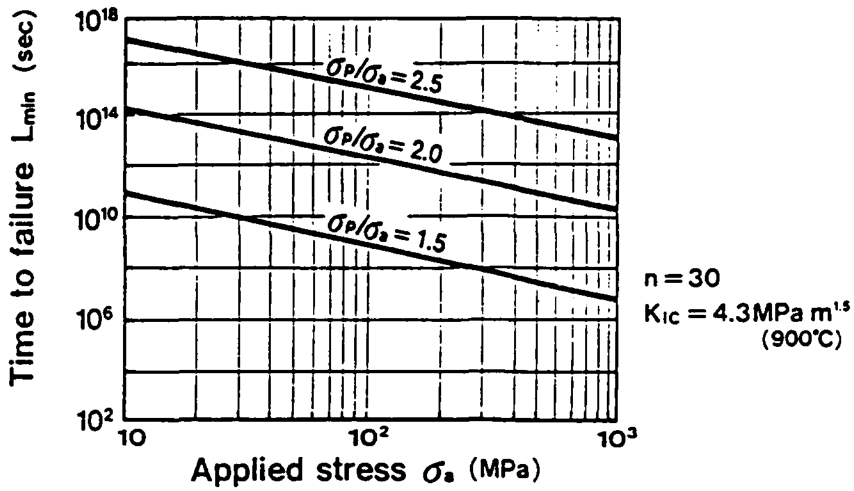


Figure 14. Proof test failure diagram for upper region in swirl chamber at high temperature.

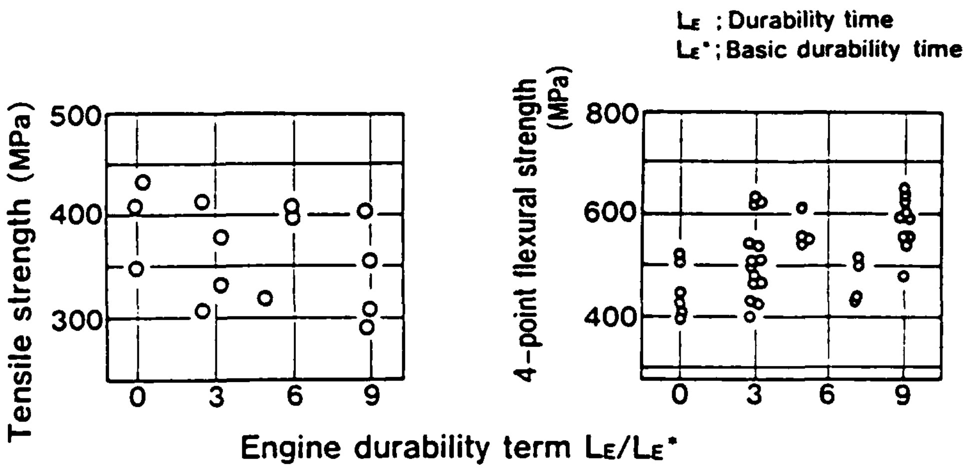


Figure 15. Strengths in upper region and lower outside of swirl chamber according to engine durability term.

Question:

In the last portion of your talk, I understood the ring test by internal pressurization. Is the bend test also a curved specimen?

Answer:

Yes, it is a curved beam bend test.

Nicholson

Professor Nicholson described his studies of composite materials based on sodium beta alumina, a refractory micalike material. The use of sodium beta alumina to toughen partially stabilized zirconia and spinel at room temperature and high temperatures was described. Interfacial morphologies were controlled in the composite by ion exchange of the beta alumina with a number of cations. Ion exchange in situ to strengthen spinel and glass was described.

Question:

Which has a higher content of sodium, the glass or the beta alumina?

Answer:

It's a soda lime silica glass of standard composition that is usually about 20 percent alkali. The beta alumina is about 10 percent. So which way does the sodium diffuse? You have more in the glass than in the beta alumina so it won't diffuse into the beta alumina because that's stochio- metric. I don't think there would be any diffusion into the glass. But in other matrices you can get sodium zirconates or sodium aluminates. You could start with potassium beta alumina. It's interesting that there are something like 36 elements in the periodic table that can exchange into beta alumina.

Comment:

I realize that your thickness of the compressive layer was determined by polishing to be about 40 microns. I think in this material the real flaw size should be much larger, at least as large as the particle, something on the order of 100 microns or so.

Reply:

The particles in this case are about 40 microns, but you put your finger on one of the problems. If you want to increase the strength, then you must make sure that inside the glass you don't have large beta alumina particles. We are trying to develop some way of putting them on the surface, only in the surface so you don't get failure from inside. I think it's possible to process the glass so that you only put beta alumina on the surface.

Srinivasan

Dr. Srinivasan provided a presentation on characterization for design and performance prediction of ceramics and pointed out that precise definition and measurement of fracture parameters are critical in design, as well as in appropriate nondestructive examination and failure analysis of components. He showed that in certain instances the mechanical and fracture properties as measured for material development are not directly applicable for design. Furthermore, in general, the existing data base is rather limited. Srinivasan discussed the various mechanical test methods and some of their limitations. Then he described tensile strength experiments. The geometry and grip design are given in Figure 16. Regarding fracture behavior he described some of the difficulties of accurately determining the necessary parameters. There are many active mechanisms, such as crack coalescence, crack blunting, oxidation, and other chemical phenomena. Attempts have been made to account for all fracture mechanisms, but the precision of the various time-temperature-stress zones is not yet adequately defined for most structural ceramics. He described the use of a precracked specimen for fracture toughness measurements. In discussing the use of finite element codes, he illustrated the possibility of under-estimating the probability of failure by not properly accounting for time-dependent phenomena.

Comment:

Many of the points that you have raised have been examined in Japan. Your last technique of introducing sharp cracks into samples has recently been developed by Nippon Steel, and I think it will be adopted as the fracture toughness standard procedure. Nippon Steel will be doing round-robin tests, and in 1 or 2 years they will probably have a very thorough study of that particular technique. So I think we are all heading in the right direction, regardless of language or geographical barriers. Also I'd like to mention that in the first part of your presentation you showed a picture of a number of samples versus a Weibull plot. As you know, Weibull parameters are dependent on the choice of estimators. What were your probability estimators?

Reply:

With regard to your first comment, Professor Matsuo, of the Tokyo Institute of Technology, also has developed similar precracking techniques. I am heartened we are all focusing on the precracking specimen and perhaps we will agree after the round-robin tests exactly how to do this. With respect to your second comment, I used the maximum likelihood estimator.

Comment:

With respect to your comments about alpha silicon carbide having two different distributions of times to failure in different types, this could be indicative of the threshold stress intensity factor below which you don't get crack growth and above which you do. So your long-time failures can be due to other causes. We have seen such data from Penn State. The other comment is with regard to introducing a crack. That's a very nice way to do it. But if you have a rising R-curve in your material, say due to bridging effects behind the crack, then this will always measure an "upper shelf" value. So one of the things you might want to add is go in and machine out part of the crack behind it but leave the tip, the sharp tip. That way you can get back down on lower parts of the R-curve. That might be a nice complement to what you are doing.

Question:

I am a little astonished that today we heard so many people arguing about the tension test. The bend test was never meant to be the very best test method! It was just an easy method. But I think you are making progress. Now what should those people who are developing new materials do? We have the problem that only small sizes of material are usually available. Let's consider the example of data generation for steel. I think more than 48 tons of steel have been used simply for strength determination! This involved testing of all sizes and shapes. If we do something like that for every developing material, where would we be? Which values are important for measuring, and how can we economically determine strength and fracture toughness? In short, which values shall we measure for developing materials, and by what method?

tests. I think that shows the problems that are under discussion now. Industry has to be sure the material will stand up properly. I don't see any test method, including the method of tension with large volume, that we can use to make all predictions. Even though fracture mechanics behavior of metals is well understood, we still rely on test pilots for airplanes. I don't think think there is a good estimation technique, even if it is large and elaborate and if the physics is complicated, for applying materials—nothing compares with the real proof tests.

Dr. Soga

Dr. Kishi's procedure is not a nondestructive test in the ordinary sense but a way of detecting small microcracks. This procedure might be considered in-between nondestructive testing and proof tests. We should look into it.

Another major area of interest would be the relationship between test specimens made for laboratory tests and test specimens taken from the real component. Some difference was suggested in Dr. Kawai's presentation. For example, in Dr. Kawai's previous work, $N \geqq 100$, while in Kishi's work $N \leqq 78$ at room temperature. Is it because some specimens were made for laboratory tests and some from the actual component? This kind of difference has to be clarified.

Professor Nicholson expanded ideas of achieving the partially stabilized zirconia type of high toughness in other types of ceramics by applying beta alumina, mica, or those kinds of materials. This has been done in several ways in Japan (e.g., Dr. Fukunowa's or Dr. Sawaoka's work on the diamond-type composite). Improving fracture toughness by means of composites seems to be the next step.

Evaluation of composite effects is very important, particularly the interface between metal and ceramic, or between ceramic and ceramic. In Dr. Nicholson's case, he found a kind of intermediate compound between beta alumina and the matrix. This kind of interfacial evaluation as well as characterization is important. These problems should be studied.

SESSION IV. ADVANCED RELIABILITY METHODOLOGY

AGENDA

The following speakers presented current state-of-the-art reliability methodologies that are commonly used, described some of their advantages and disadvantages, and described advanced methodologies that could be applied.

- Yo Tajima, NGK Spark Plug Co., Ltd., Research Department, NTK Technical Ceramic Division, "Reliability Technology for Ceramics"

- Yotaro Matsuo, Tokyo Institute of Technology on Statistics, "Flaw Size and Strength Distribution of Ceramics"

- Isao Oda and T. Soma, NGK Insulators, Ltd., Materials Research Laboratory, "Reliability and Lifetime Prediction of Ceramic Components"

- Nancy J. Tighe, National Bureau of Standards, "Microstructural Damage in High-Temperature Fracture and Creep"

- Hans Larker, ASEA Cerama, Sweden, "Some Views on Mechanical Testing Methods and Their Relevance to Process and Product Development"

- Gunter Petzow, Helmut Schubert, and Peter Greil, Max Planck Institute, Stuttgart, "Defect Formation During Powder Processing and Sintering of Ceramics"

COMMENTS

Tajima

Dr. Tajima described studies of silicon nitride materials conducted at NTK Technical Ceramics Division, including materials processing studies and turbocharger rotor development for Nissan Motor Company. Effects of starting powder and processing route were addressed first. Two processing routes were studied, namely conventional processing starting with silicon nitride powders and a postsintering route that starts with silicon powder. For the conventional route, three types of additives (Y_2O_3, CeO_2, or Sc_2O_3) and three types of silicon nitride powder were used. Results of the silicon powder characterization are shown in Table 1, and room-temperature flexural strength and fracture toughness as well as 1,300 °C flexural strength are summarized in Figure 17. There is no doubt that the mechanical properties are affected by powders and processing route.

Regarding the Nissan turbocharger, gas pressure sintering was selected as the processing route and a new shaping method combining injection molding and cold isostatic pressing was developed. Figure 18 presents strength data for the rotor materials and compares it to flexural strength measurements on cut-up turbochargers, indicating that the process is fairly homogeneous.

Question:

You have discussed your research in new materials, but what about raw materials?

Table 1. Characterization of Silicon Nitride Powder

Item	Silicon Nitridation (A)	Vapor Phase Reaction (B)	Silica Reduction (C)
BET, m^2/g	20	7.1	10.9
FSSS, μm	0.50	0.70	0.90
α Content, %	94	96	99
Chemical Analysis			
Si, %	59.2	59.4	59.2
N, %	38.4	39.4	38.0
O, %	1.46	0.46	1.79
C, %	0.30	0.03	0.75
Free SiO_2, %	0.24	0.36	1.04
Fe, ppm	80	4	160
Ca, ppm	9	<1	220
Al, ppm	130	6	92
Mg, ppm	20	<1	8

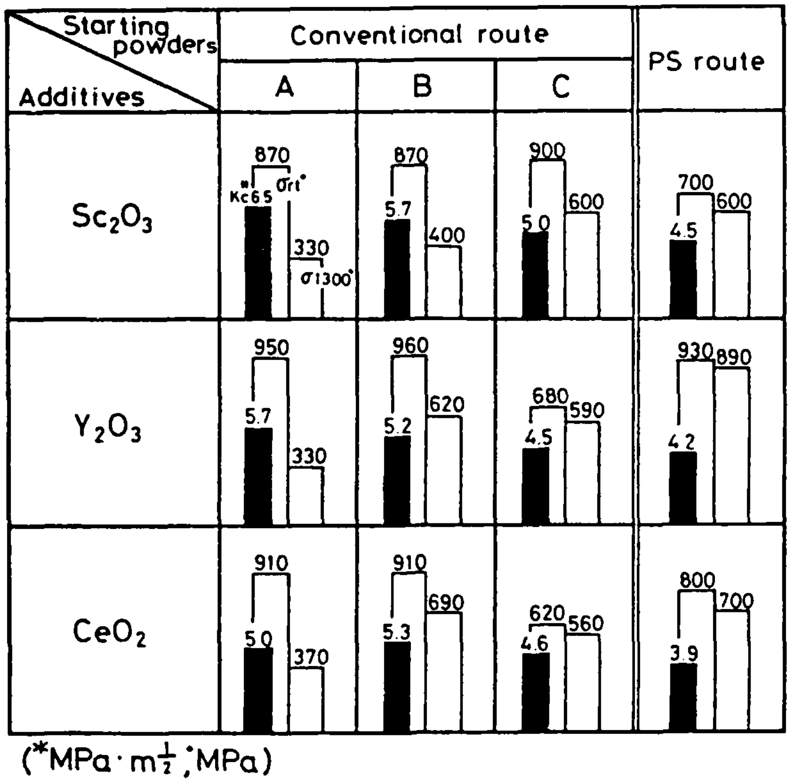


Figure 17. Flexural strength and fracture toughness of hot-pressed material.

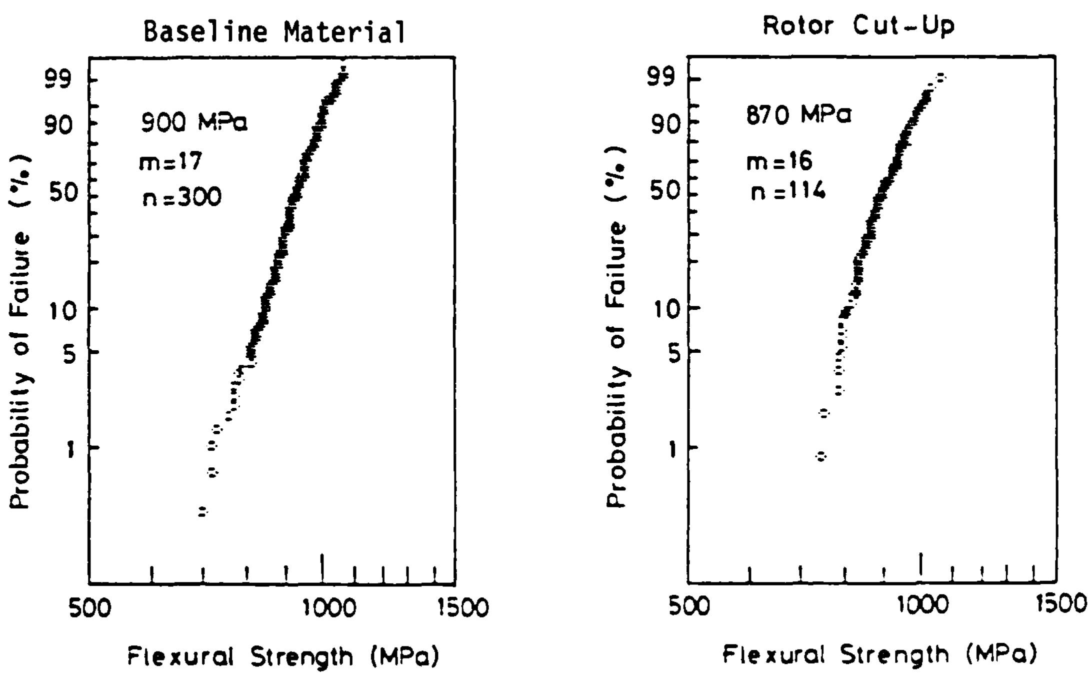


Figure 18. Strength distribution of GP-SSN.

Answer:

Very different properties can be obtained depending on the raw materials used. The fundamental question is which factors contribute to the performance of the component? These factors include chemical properties, impurities, grain size, and grain size distributions. We are currently working on that kind of information.

Question:

Have you conducted any cyclic fatigue tests? You showed the results of static fatigue tests on the rotors.

Answer:

We have conducted cyclic fatigue tests at room temperature and the results were consistent with the results from static fatigue and also dynamic stress tests. We have not carried out cyclic fatigue tests at higher temperatures.

Comment:

Please comment on the relative costs of the different additives.

Reply:

Alumina, magnesia, yttria, and other rare earth oxides are usually used; for example, yttrium oxide is quite extensively used by many companies. It is relatively expensive, especially as the price of silicon nitride powder is now decreasing. For cost reduction we might have to look at lower cost additives in the future.

Matsuo

For a number of years now Professor Matsuo has been applying probabilistic theories to develop insight into flaw size, fracture toughness, and strength behavior of structural ceramics. In this paper, based on a variety of proposed interrelationships and experimental data, he suggested several new methods of estimating Weibull parameters. In particular, he began by quantitatively examining the effects of stress distribution, Weibull's shape parameter, and specimen volume on flaw size distribution. His calculations are based on extensive testing of 3- by 3- by 20-mm three-point bend specimens where flexural strength, fracture toughness, fracture location, and flaw sizes were observed. Fracture toughness was estimated by an indentation technique. Results of these calculations are shown in Figure 19.

This calculation is based on the simultaneous probability density function of flaw size, d_c, at the fracture origin and fracture location. The distribution function of flaw size at the fracture origin in a tensile specimen is shown in Curve II. Referring to Figure 19, Curve II shifts to larger flaw sizes, which corresponds to the fact that flaw sizes that initiate fracture under uniaxial tension are relatively larger than those under three-point bending. Considering the effect of Weibull parameter m_1, the theoretical curve shifts to the larger portion of flaw sizes as m_1 decreases, which corresponds to the relationship of m_1 to scattering of flaw sizes.

Matsuo explored the influence of volume change on probability density distribution of flaw size. The calculations for three-point flexure and for uniaxial tension are shown in Figure 20. A most interesting result is that the mode of the three-point bend test is about 20 microns smaller than the tensile geometry he studied, which may be of significance in planning for experiments for nondestructive development.

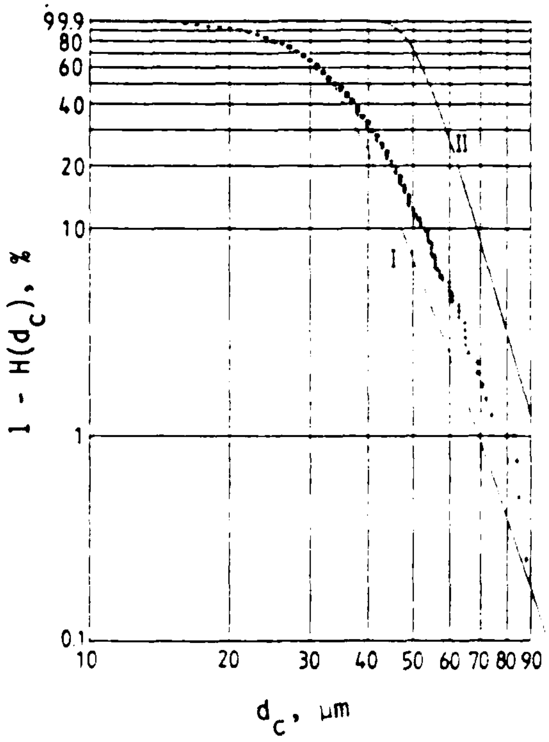


Figure 19. Cumulative distribution function of flaw size at fracture origin. + signs indicate the observed data of HP-Si_3N_4 subjected to three-point bending load. Curve I is the theoretical curve for three-point bending. Curve II is the theoretical curve for uniaxial tension.

Matsuo also studied the relationships of grain size dependency and fracture based on two-dimensional penny-shaped cracks and the appropriate equations. Results for the simultaneous probability density function under three-point bend testing are shown in Figure 21. As indicated by the solid line, this approach overestimates the flaw size.

In Figure 22, the histogram of flaw sizes is compared to two types of calculations. The closed circles are based on earlier studies, while the open circle estimates are based on the simple expression $K_C = K_{IC} = 4.06 \sqrt{m}$ (MPa). Note that the open circle results overestimate the flaw size in the region $d_c > 50$ microns and would therefore be less desirable in reliability calculations.

Matsuo presented a new approach to estimating Weibull shape and scale parameters using only flaw size data in uniaxial tension and measured fracture toughness. Using similar probability treatments, flaw size estimates before and after nondestructive inspection (NDI) were estimated. To a certain extent the flaw size data agree with the NDI data. Removing the smallest size flaws, as by deleting with an imagined perfect NDI screening, brings the results into better coincidence.

In summary, Matsuo has proposed a number of useful perspectives in treating experimental results via probability theory. If it were possible to accurately measure flaw size distribution by means of nondestructive testing, and to accurately measure fracture toughness, then the approaches suggested could be used in practical ways to thoroughly assess the potential of actual component hardware. In considering the methodology, however, it is well to recall that all the calculations are based on two-parameter Weibull distributions and relatively simple formulations. It would be interesting to conduct such calculations with nonparametric methods and to use sensitivity analysis along with confidence intervals to accurately assess the methodology.

Question:

Does the nondestructive testing you referred to include proof testing?

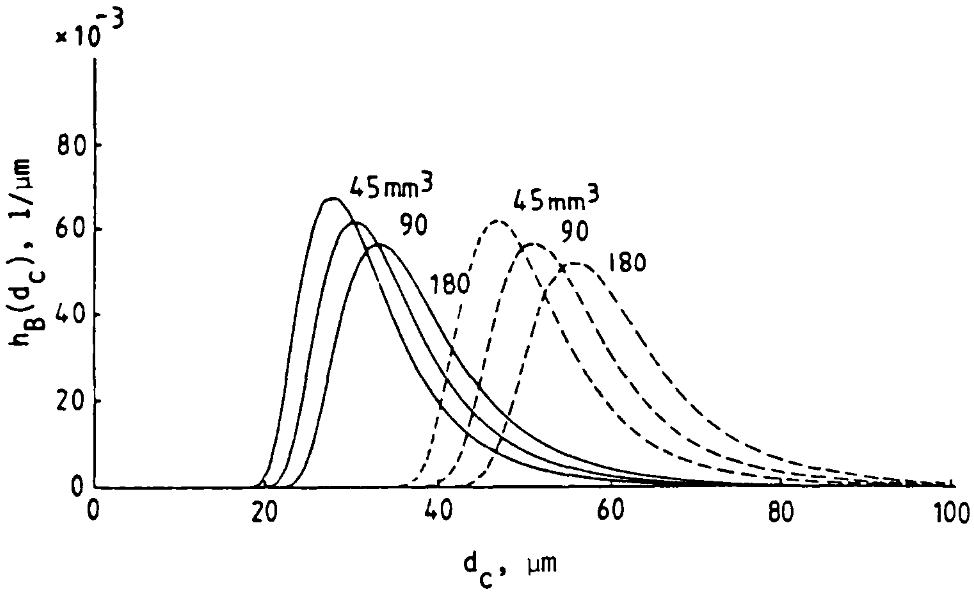


Figure 20. Effect of volume change on the probability density function of flaw size. Solid lines represent three-point bending, and dotted lines represent uniaxial tension.

Answer:

No, only nondestructive testing. However, NDI can have a one-to-one correlation with proof testing, as we have concluded from our research.

Question:

In the frequency distribution you mentioned, the majority of the flaws were, of course, on the surface. Now in many of the ceramics the type of flaw that is located on the surface influences the strength greatly. That is, even in hot-pressed silicon nitride the machining flaws on the surface behave differently than the processing flaws that are not machining related. Was flaw fractography done on those 400 or 415 samples? Were they machining-related flaws? This means residual stresses might arise. Can you comment on that?

Answer:

The experimental data had indicated about 20 percent failures due to surface flaws; therefore, residual stress induced by machining is not negligible. At this time we cannot include it in our theory. As stated in the previous work, we include surface or internal flaws simultaneously in our theory.

Question:

How practical would it be to implement your methods into finite element approaches?

Answer:

Perhaps it would be available for finite element methods.

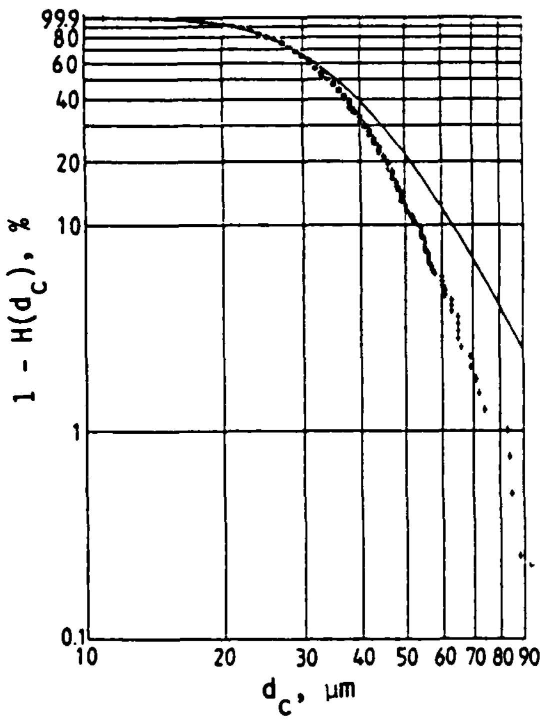


Figure 21. Cumulative distribution function of flaw size. + signs indicate observed data of HP-Si_3N_4 subjected to three-point bending load, and the solid line represents a theoretical curve.

Oda and Soma

Oda and Soma presented their approach to reliability and lifetime prediction in terms of a so-called fracture map. The stress and temperature distributions of typical turbocharger rotors and ceramic piston caps were estimated by finite element analysis. These calculations were compared to experimentally determined long-term durability data on ceramic materials. In their discussion, the authors consider fast fracture and static fatigue failure according to the following equations.

Allowable stress for fast fracture, σ_{al}, is given by:

$$\ell n \ell n \left(\frac{1}{1-F}\right) = m \, \ell n \left[\frac{\sigma_{al}}{\overline{S_{tp}}} \Gamma(1 + 1/m)\right] + \ell n \left[\frac{V_{e(comp)}}{V_{e(tp)}}\right] \quad (1)$$

where: F = fracture probability

$\overline{S_{tp}}$ = average strength of test specimen

V_e = effective volume

Allowable stress for static fatigue failure, taking into account the effective volume and failure probability, is given by:

$$\ell n \ell n \left(\frac{1}{1-F}\right) = \frac{m}{n-2}(\ell n \, T_f - \ell n \, B + n \, \ell n \, \sigma_{al}) - m \, \ell n \, \overline{S_{tp}} + \ell n \left[\frac{V_{e(comp)}}{V_{e(tp)}}\right] + m \, \ell n \, \Gamma(1 + 1/m) \quad (2)$$

where T_f is required lifetime and n and B are constants relating slow crack growth.

Oda and Soma treat creep failure and oxidation failure using an Arrhenius-type exponential formulation. Creep failure is assumed to occur when the local maximum strain becomes equal to a specific value. For creep behavior a power law form is used.

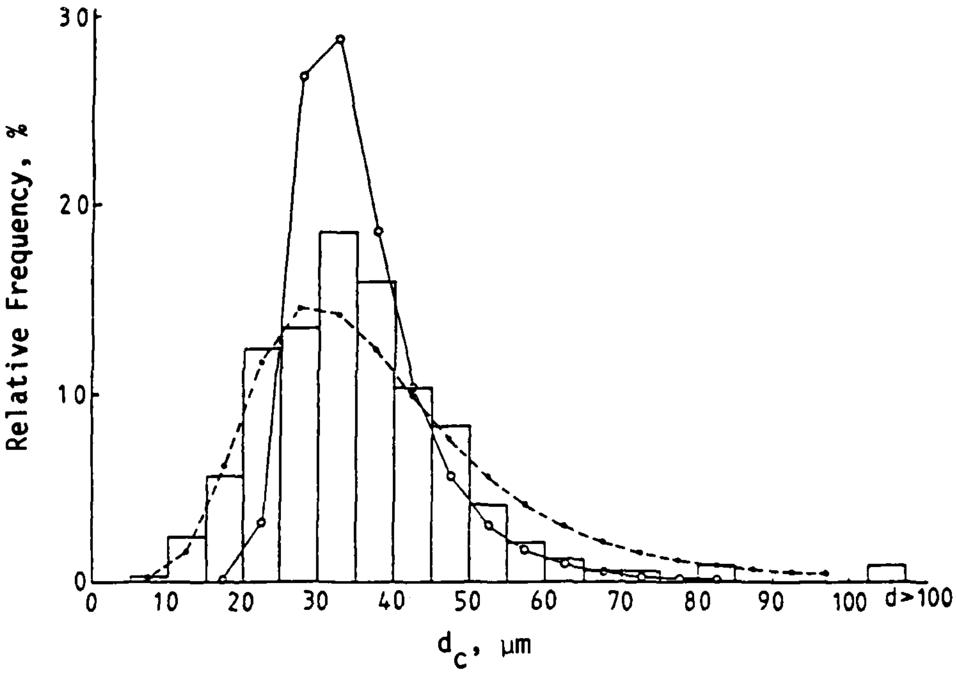


Figure 22. Histogram of flaw size for three-point bending.

$$\sigma_{al} = \left(\frac{\varepsilon_f}{C\ T_f}\right)^{1/N_c} \exp\left(\frac{\Delta E_c}{N_c\ R\ T}\right) \qquad (3)$$

where: ε_f = critical strain

C = constant

N_c = creep exponent

ΔE_c = activation energy for creep

Weight gain and oxidation are proportional to the square root of exposure time, and the allowable stress for oxidation exposure is stated as:

$$\sigma_{al} = \frac{K_{1c}}{Y}\left(\frac{\lambda_1\ \lambda_2}{W_o}\right)^{1/2} \cdot T_f^{-1/4} \exp\left(\frac{\Delta E_o}{2\ R\ T}\right) \qquad (4)$$

where: K_{1c} = fracture toughness

Y = flaw geometric constant

$W_o, \lambda_1, \lambda_2$ = constants

ΔE_o = activation energy for oxidation

Oda and Soma presented a fracture map (Figure 23) for 5,000 hours of exposure and suggested that the fracture probability for a particular ceramic piston cap is much less than 1 percent.

Question:

In the ceramic piston cap, or the turbocharger, how did you obtain the effective volume?

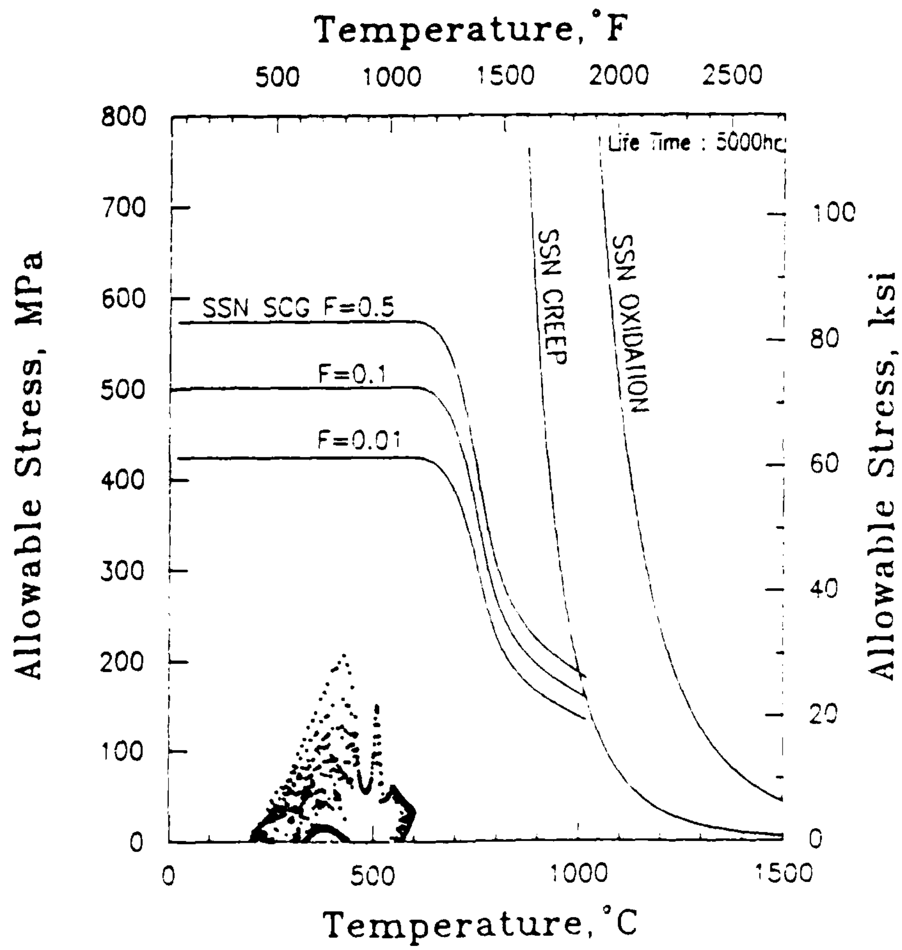


Figure 23. Fracture map of a ceramic piston cap for adiabatic diesel engine (BMEP: 11.2 kg/cm^2).

Answer:

We obtained it from three-dimensional finite element analysis based on Weibull theory.

Question:

You have estimated or assumed a 5,000-hour lifetime. How did you calculate that?

Answer:

We selected a certain time and used slow crack growth data, based on the old data and Weibull type theory, to obtain such results.

Comment:

When you think of the real turbocharger, the most severe points are at the juncture with metal.

Reply:

We need to have better fits with the experimental results. There is no doubt the joint presents problems.

Tighe

Dr. Tighe presented a summary of her studies via the analytical scanning transmission electron microscope to provide direct evidence for a number of specific creep processes in several types of silicon nitride and silicon carbide and for strength degradation by corrosion in molten sodium carbonate. Both chemical and microstructural aspects were discussed for bonding phases, inclusions, and surface layers in nitrides and carbides after exposure to thermal and mechanical stresses and to corrosive atmospheres. Dr. Tighe described the observed microstructural changes and related them to specific deformation mechanisms.

Tighe pointed out that silicon nitride and silicon carbide ceramics are processed with additives to promote sintering and to develop desired microstructures. After processing, these sintering aids, which remain between grains and at triple junctions as components of amorphous or crystalline bonding phases, dominate the creep mechanisms. Furthermore, she noted that such behavior is a natural consequence of the fact that creep is often a desintering process and the bonding phases themselves are chosen because they react at lower temperatures than the matrix grains. She pointed out that high-temperature exposure can produce an initial apparent strengthening in both silicon nitride and silicon carbide since some surface defects are healed by the formation of a silica scale. However, prolonged exposure allows deep penetration of oxides formed along grain boundaries, cavitation along boundaries, reactions with internal inclusions, and eventual degradation of strength. Creep in silicon nitride and silicon carbide involves cavitation and crack propagation within the bonding phase when the temperatures are below those necessary to cause plastic deformation within the grains.

Four types of commercial ceramics were discussed, namely hot pressed silicon nitride (HPSN) containing either magnesia or yttria additive, sintered alpha silicon carbide, and siliconized silicon carbide. HPSN of the first type usually has an amorphous magnesium silicate bonding phase that forms a film about 1 nm thick between the grains and fills any void spaces at triple junctions of grains. Inclusions of WC, WSi_2, and SiC were found in both types of nitrides. The alpha SiC was made with a polymeric sintering aid that tends to decompose to carbon during sintering and subsequently to form some graphite fibers at the triple junctions and leave some graphite platelets within the grains. The Si/SiC ceramic contained silicon and silicon carbide particles as an interpenetrating, inhomogeneous network of phases.

Creep and corrosion damage and mechanisms were discussed in these four types of materials. It is interesting to this observer that no accurate theoretical models yet exist to describe the spatial distribution, growth, and general behavior of these various mechanisms. Such models would seem to be a prerequisite to adequately predict the long-term, time-temperature—stress—strain—dependent behavior of high-performance ceramics.

Question:

When we consider the criterion of reliability at high temperature in ceramics, which will become the main parameters? Deformation? Fracture toughness? Some people in the field of fracture mechanics would like to use the concepts of macroscopic crack propagation. But as far as I see in your presentation, I believe that deformation itself will be a dominant factor to control the criterion of fracture.

Answer:

It depends somewhat on the temperature. Many of these materials were tested at high temperatures where creep could occur. That's beyond the limits of typical use. At lower temperatures, one would want to consider fracture more, perhaps. However, even at lower temperatures, the microstructure will change, so the fracture that happens in the room-temperature tests is different than the fracture that happens at high temperatures, in many ceramics. Obviously, it's very important to identify if there are any changes in failure mechanisms. I am not a theorist, but there probably has to be a modification of theory that includes a change in flaw types at high temperatures.

Larker

Dr. Larker started his presentation by reminding the participants that test methods should be selected depending on the purpose of the testing, and this is specially true for ceramics wherein multiple flaw distributions are more common than not. He recommended that tension tests be used to obtain design data since this type of specimen is very efficient in revealing the large defects that usually cause failures in components such as turbine wheels. On the other hand, failure-initiating defects that typically occur in actual hardware are rarely found in the fracture surfaces of three- or four-point flexural test specimens. In the development of processing procedures and equipment, particularly with injection molding, the possible introduction of large strength determining defects, or strength limiting defects, is a very important consideration. Therefore, tensile test methods to stress fairly large volumes of materials are useful. However, three-point bend tests are better suited to monitor results of microstructural developments in high-strength ceramics. As for four-point flexural tests, they are often dominated by surface-dependent phenomena.

Larker also indicated that most mathematical descriptions of fracture statistics presently are based on the weakest link concept, which simply states the entire body will fail when the stress at any defect is sufficient to cause unstable crack propagation at that defect. While no weakest link distribution function that is universally acceptable has been identified, the two-parameter Weibull distribution has become very popular because of its relative simplicity and reasonable results in describing most fracture data. Furthermore, most treatments of fracture statistics assume that a single distribution of flaw types exists and is uniformly present throughout the material and that different pieces of the same material contain the same flaw distribution. But this is rarely the case in real components. Regarding multiple flaw distributions, Larker cited the work of C. A. Johnsson, General Electric Corp., and his treatment of three modes of multiple flaw distributions, namely concurrent, exclusive, and partially concurrent.

In this presentation some results were presented for several types of tension tests as well as flexure experiments. Figure 24 illustrates a 9.5- by 9.5- by 120-mm bar that is spun to failure. Figure 25 shows a tension test that uses hydrostatic pressure on a 9.5-mm bar with bonded end caps. In Figure 26, some results obtained by this hydrostatic tensile test method are compared with results obtained in three-point bend tests.

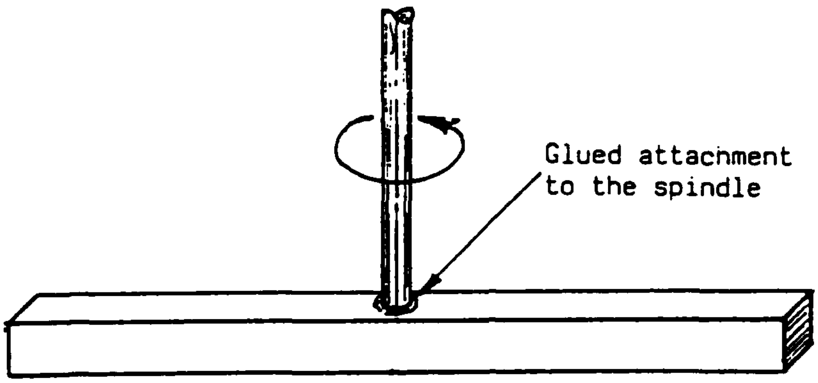


Figure 24. Tensile testing of a 9.5- by 9.5- by 120-mm silicon nitride bar. It is spun to fracture in a vacuum spin pit.

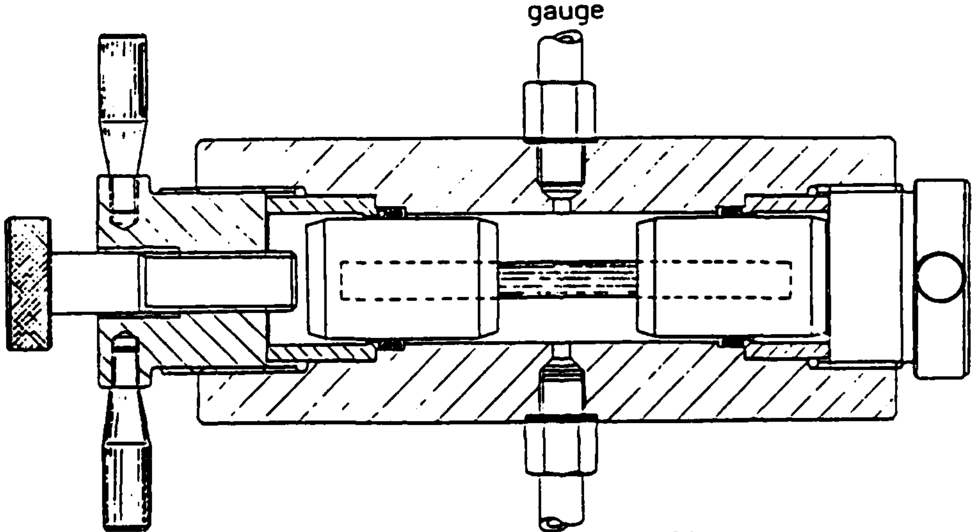


Figure 25. Cell for low-cost tensile testing.

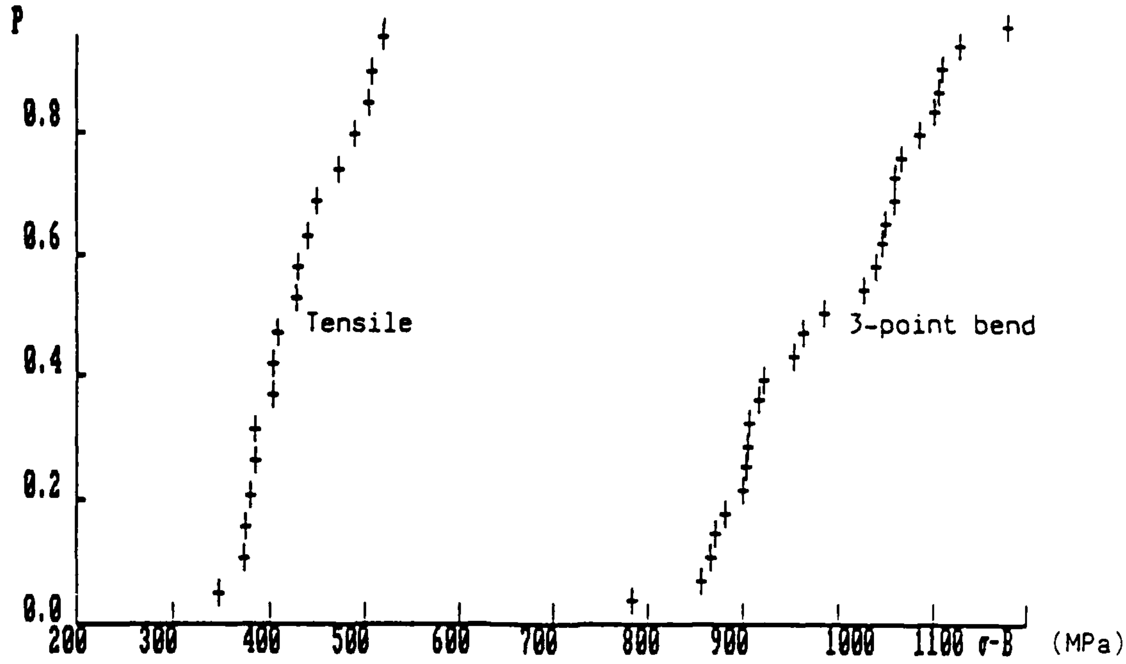


Figure 26. Results from tensile tests (left) of 0.95-mm rods and three-point bend tests of 3- by 3- by 30-mm bars with 20-mm span (right). Material: HIPped UBE SN-10 with 2.5% yttria. Results: x = 428 MPa and m = 8.8 (tensile); x = 987 MPa and m = 11.1 (three-point bend).

Comment:

Just a comment on three- versus four-point testing. We always tell a student four-point, never three-point tests. The bending moment diagram as you know is triangular in three-point tests and you are stressing at one location. If you are really lucky, you get a high-strength bar, and usually you get at least 10-percent higher values in three-point bending.

Reply:

The problem with four-point bending tests is that most often with this mode of testing you find a machining flaw and this is characteristic for the machining method of that particular material. Maybe it provides very little information on material property development, and maybe you are at that time more interested in the effect of trying a new additive or other process change to help develop a better material. Of course, four-point testing may help you to discover a better machining technique. So ideally, from my view, to help develop materials I would propose three-point testing with an edge on the loaded side. Then, of course, you have to work very hard to take away those defects that cause fracture in very large volumes. These are the factors causing differences between components and small test specimens. But, in four-point testing, you may not know what you are doing in your microstructural development.

Comment:

Would you comment on biaxial tensile testing for the purpose for which you refer to three-point testing. In biaxial flexural testing you can test an unmachined surface, even a slightly warped surface, at some loss in accuracy for the results.

Reply:

I have no experience in that. I can only say that might be an even better proposal.

Schubert

Dr. Helmut Schubert talked about defect formation during powder processing and sintering of ceramics. In particular, his presentation covered his early studies on flaw formation during fabrication of Al_2O_3-ZrO_2 and tetragonal zirconia. Examples discussed were simple shaped components (i.e., discs, cylinders, and plates) prepared by isostatic pressing and slip casting techniques. He illustrated the formation of critical defects, such as obvious cracks and similar flaws, pores, and pore clusters, during sintering and substeps in processing.

CHAIRMEN SUMMARY COMMENTS

Dr. Edward Lenoe

Session IV, Advanced Reliability Methodology, covered the whole range of consideration of factors that influence reliability methodology.

Professor Matsuo presented a very excellent development of theoretical approaches to treat strength and spatial distribution of multimodal functions. This has, I think, many implications for the future. Currently, two-parameter Weibull distributions are the common technique, and it is very difficult to get people to use the kinds of theories that Dr. Matsuo has developed. However, he has put it in such a formulation that people who do finite element calculations will now have this kind of potential. So this, in a way, represents quite advanced reliability methodology techniques, the kinds of things that should be applied. I just wanted to make one comment with regard to that type of calculation, and that is regarding another area of deficiency that has to deal with lack of putting confidence intervals on the resulting calculations. In other words, we ought to quote results in terms of not only a probability value but also a confidence interval. We really need to do that to make a correct and meaningful statement about the life estimate or safety of the component.

The next two papers had some similarities in that they represented state-of-the-art approaches for processing, quality assurance, and the application of reliability methodology. Starting with fundamental processing considerations, Dr. Tajima gave an excellent presentation that covered the results of using different additives, and then he proceeded to describe the development efforts at his organization. Oda and Soma co-authored a very complete status review of the typical kinds of engineering approaches and applications and discussed their extensions into a fracture mapping technique based on three-dimensional finite element analysis.

The next paper by Dr. Tighe, from the National Bureau of Standards, was an excellent review of microstructural aspects and the defects that are generated in the process of failure for a whole range of ceramic materials. I was glad to see this paper in this session because it provides insight for theoreticians. This paper presents very strong physical, visual evidence of the kinds of things we are trying to detect and to model.

Dr. Larker's presentation had one humorous aspect in the sense that he talked about fundamental development of the Weibull theory by his countryman back in 1939 and he mentioned that Professor Weibull is probably turning in his grave because he would not approve of the unconstrained use of the two-parameter Weibull model, which is the most commonly used model. He also presented a nice series of suggestions as to test methodology, and ASEA has a clever way of running a hydrostatically based tension test on small uniaxial specimens. I know, based on work by Barratta, that the method can also be extended to compression and shear testing by changing the pressurization scheme and the end fittings. I believe it can be developed for high temperatures as well.

The last paper in the session was presented by Dr. Schubert. It provided some good insight into the physical processes that generate defects in ceramics, and he illustrated a number of important physical insights. One thing that he mentioned that has not received enough attention is the residual stresses that are generated in the actual production process. There should be more work going on in trying to minimize and to measure these kinds of stresses. I believe, as Dr. Schubert mentioned, that in a number of cases failure to properly predict component life may be traceable back to the presence of such unaccounted for residual stresses.

To summarize, Figure 27 shows one of the problems that we have in dealing with advanced reliability methodology. This figure shows flexural stress versus time to failure for three types of specimens: small, medium, and large beams. The beams range in size difference by a factor of 40. The largest is about 40 times that of the smallest in area or volume. Referring to the results, it appears there is a time-dependent size effect. Attempts to explain these few results have not been successful using currently applied methods.

Professor Matsuo

This session was closely related to Session II, particularly the papers on the effect of temperature changes on microstructures and on quantitative measurements of mechanical properties and their quantitative analyses. These quantitative analyses must be fed back through a feedback process to enable us to carry out a more sophisticated form of processing. Dr. Tajima's turbocharger success was an extremely important landmark, and we all have been encouraged by Dr. Tajima's success in reliability technology.

SESSION V. APPLICATIONS TO MECHANICAL PARTS

AGENDA

In this session, the following industrial ceramic applications were described, including experiences in applications, problems in designing, and structural differences as contrasted with equivalent metal products.

- Yoshiteru Kido, Hamada Blower Co., Ltd., "Advanced Ceramic Systems for Blower Fan Applications"

- Haruyuki Ueno, Takashi Hiragushi, S. Fujimoto, and Y. Naruse, Kurosaki Refractories Co., Ltd., "Application to Large Size Heat Exchangers"

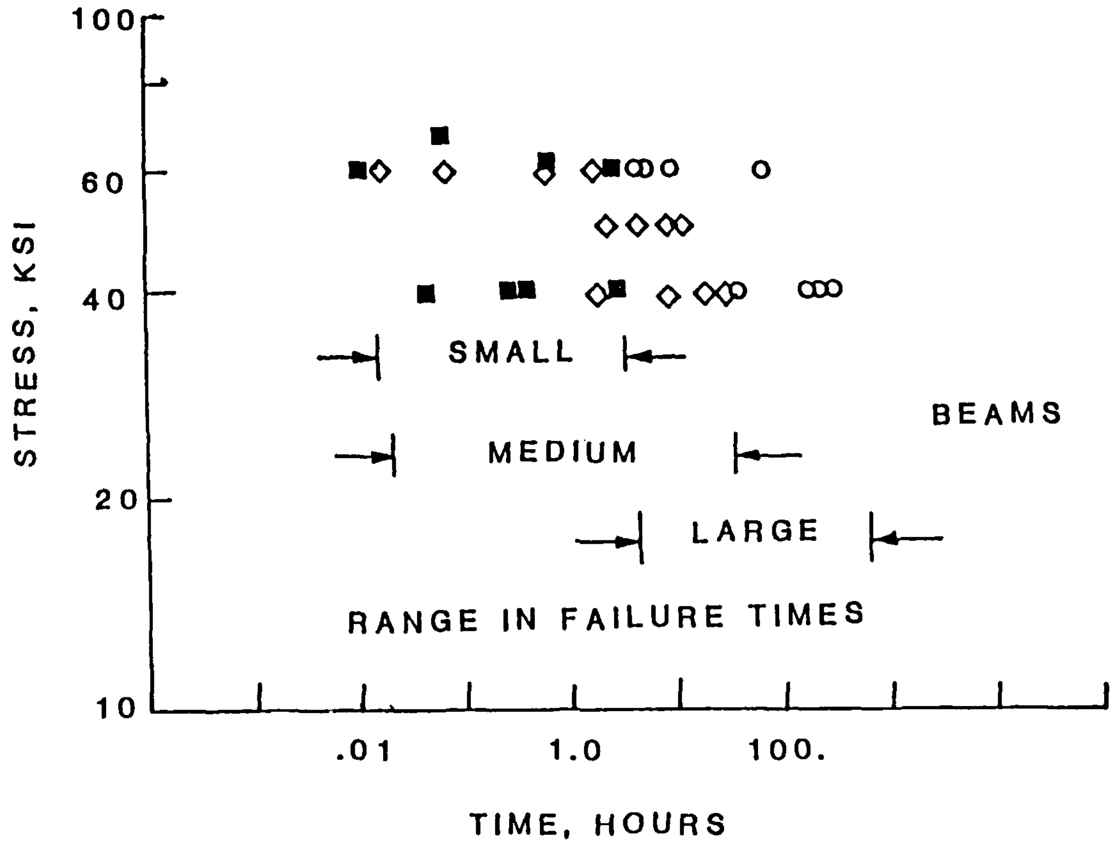


Figure 27. Stress versus time for small, medium, and large NC-132 beams.

- Shigemi Suzuki, Toto Co., Ltd., "Application of Ceramic Boards to Air Bearing Technology"
- John B. Wachtman, Jr., Richard A. Haber, and Richard M. Anderson, Center for Ceramics Research, Rutgers University, "Mechanical and Other Properties of Glass-Bonded Ceramic Composites"
- Joseph Wurm, Head of Advanced Materials Research, Brussels, The Commission of the European Communities, "European Communities Sponsored Research in Technical Ceramics"

COMMENTS

Kido

Yoshiteru Kido reported that over 100 fans in Japan and overseas have been treated with wear-resistant ceramic coatings. Because of the high concentration of airborne dust particles, blower fans used in steel making, as well as in cement and power plants, are subjected to wear and erosion problems. This is a costly matter because the blades and hub regions of the fans require frequent repairs. The fan selected for this study was a turbo model with vane and wing type blades having an efficiency of 80 to 85 percent.

Numerous advanced ceramics are known for their hardness and excellent abrasion and erosion resistance. Kido reported on tests with alumina, silicon nitride, silicon carbide, and zirconia. Procedures for attaching the ceramic protection were based on finite element analysis to minimize interfacial stresses. The most difficult problem involved selection of adequate adhesives to withstand temperatures ranging up to 250 °C at the interface. Several types of epoxy cements were tried but were found to be inadequate. A silicon-based adhesive, however, proved successful. For example, a steel company floor "sweeping" fan, which has operated for 1 year, was described. Silicon nitride was used for fan blade tips and alumina was used in other regions. Only slight wear was evident at the ceramic-protected tips and there were minor signs of cracking and debonding. Significant increases had been achieved in reducing downtime.

Kido described numerous examples of fans, including a so-called blast furnace cast flower dust collection fan, a waste heat recovery fan, and a large fan used in a cement processing plant. Figure 28 is a schematic of one type of ceramic protective system for an impeller fan.

Ueno

Ueno discussed the use of ceramic materials in design and the test of a large heat exchanger. The materials used were composites of silicon carbide and silicon nitride. Table 2 lists the manufacturers' data for the composites. The heat exchanger was designed using finite element analysis, and experiments were conducted to verify heat recovery potential and to demonstrate durability as an assembled unit. At waste heat recovery gas temperatures of 1,200 °C, stresses were calculated to be 3 to 7 kg/mm². At waste gas temperatures of 1,400 °C, the maximum thermal stress was calculated to be about 23 kg/mm², which is about the same as the material strength at that temperature. Experiments at this temperature resulted in hairline cracks at the anticipated maximum stress location.

Question:

What is the maximum temperature that you can use?

Answer:

For the material itself, I am sure 1,500 °C would be no problem. But there are various limitations because of the structural design. For example, at the juncture area (the connecting area) there may be a problem. As I mentioned, 1,200 °C is the normal operating temperature for which the material was designed, and, of course, it can go up to about 1,300 °C. The material itself can survive until 1,500 °C.

Question:

Is the lower part free?

Answer:

Yes, but because there are two parts we have other limitations.

Suzuki

Shigemi Suzuki reported on the use of alumina in air bearing boards. This application resulted from the trend towards ever-increasing high density packing of information on magnetic, semiconductor, and optical memory devices, which necessitates high precision machining and inspection.

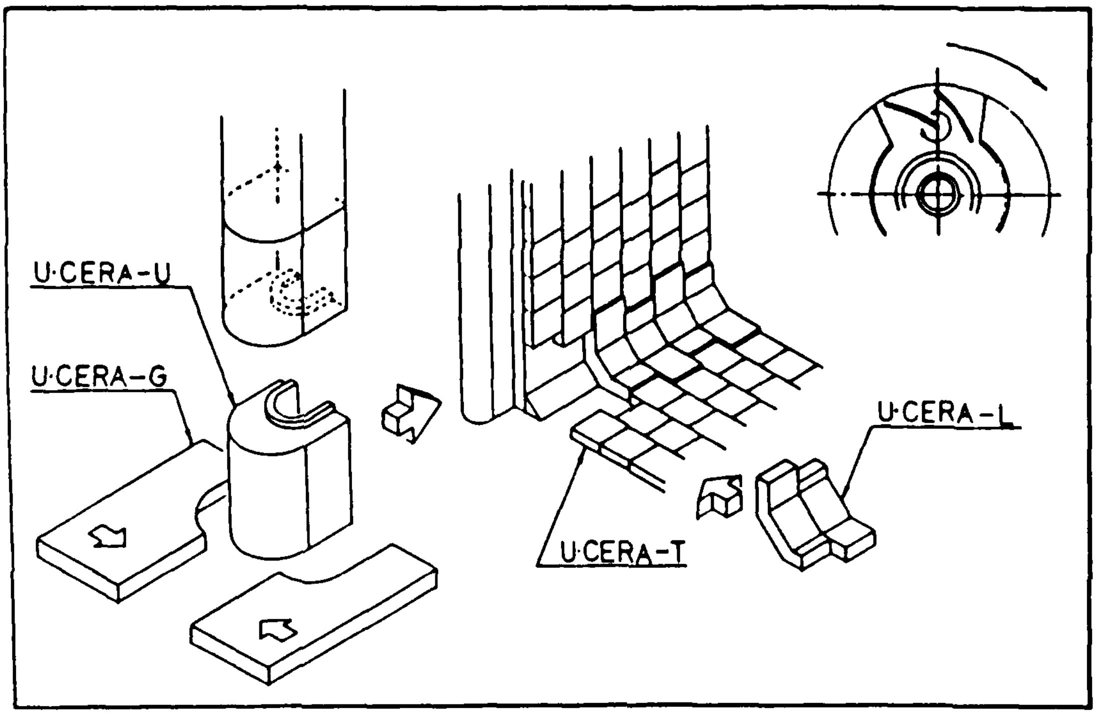


Figure 28. Detailed view of impeller inlet part.

Because of their hardness, corrosion resistance, and high specific stiffness, alumina ceramics are well suited for air bearings. In comparison to metal components, Suzuki demonstrated that alumina components are lighter and give improved mobility and overall improvements by factors of 2 to 3 over conventional systems. For example, Figure 29 compares metal and ceramic displacements in guide shafts. Suzuki described slip cast alumina measuring tools, guides shafts, air slides, and X–Y tables. Regarding measuring tools, straight edges of 2 meters length can be produced with the straightness of 1 micron. Figure 30 compares the vertical straightness of metal and alumina tables. High–alumina ceramics have excellent room–temperature stability and present technology is capable of producing surface plates of 1 by 1 meter with a surface flatness of 1 micron. Theoretical analysis shows that the lower mass of ceramics leads to higher frequencies of natural vibration, which leads to higher servo gain and improved positioning control.

Question:

Is this a wear problem? Can you use a lower modulus, lower expansion ceramic?

Answer:

That is difficult since stiffness is a requirement from other system constraints.

Table 2. Properties of Kuroceram-N

Item	KCM-N	KCM-NU
Bulk Density, g/cm³	2.80-2.83	2.70-2.80
Open Porosity, %	0.3-1.0	8-12
Three-Point Bending Strength, MPa		
Room Temperature	372-392	294-343
1,300 °C	372-392	294-343
Weibull Parameter	18-21	16-18
Young's Modulus[a], GPa		
Fracture Toughness, $MPa{\cdot}m^{1/2}$	6.2-6.5	5.0-5.6
Vicker's Hardness, GPa	7.8-9.8	6.8-8.8
Thermal Shock Resistance, °C	800-900	800-900
Coefficient of Linear Thermal Expansion, 1/°C	3.1×10^{-6}	3.1×10^{-6}
Thermal Conductivity, cal/cm•s•°C		
Room Temperature	0.036	0.030
500 °C	0.033	0.027
1,000 °C	0.030	0.022

[a]The Young's modulus of KCM-NU and -N is smaller than that of other ceramic materials, thus showing a specific stress dependence.

Wachtman

Professor Wachtman provided an interesting report on his studies of glass-bonded particulate composites. In this paper, the effect of composition, processing, and volume fraction of bonding glass on mechanical properties was studied for glass-bonded alumina. The effect of varying the ratio of cordierite to mullite using small amounts of bonding glass was also described. A mullite-cordierite-glass system was chosen because of its potential for substrate applications. For instance, cordierite ($2\ MgO - 2\ Al_2O_3 - 5\ SiO_2$) has a lower dielectric constant ($K = 5$) and thermal expansion than the traditionally used substrate (e.g., alumina ($K = 9$)). Since it has inferior strength, mullite was chosen to strengthen it. In the study, five types of glass were used, with thermal expansion ranging from less than to greater than that of alumina. Three processing techniques were used: dry pressing and sintering, slip casting and sintering, and prereaction followed by slip casting and sintering. Prereaction was used to improve alumina/glass dispersion.

Each composition was processed into 1-inch-diameter discs and 3-inch-long bars. Mechanical and thermal properties were then evaluated. This included thermal expansion, hardness, fracture toughness via Vicker's hardness, and biaxial flexural strength. Modulus was determined ultrasonically.

For the alumina-glass composites, the processing conditions and the relative thermal expansions of the glass versus the alumina had strong effects on the strength. For instance, prereaction gave significantly higher strengths for composites with less than 30 weight percent glass. At 10 weight percent glass, the strength was 61 ksi with a glass whose thermal expansion was less than alumina. On the other hand, two glasses with expansions larger than alumina gave strengths of 105 and 95 ksi, respectively, for the same 10 weight percent glass.

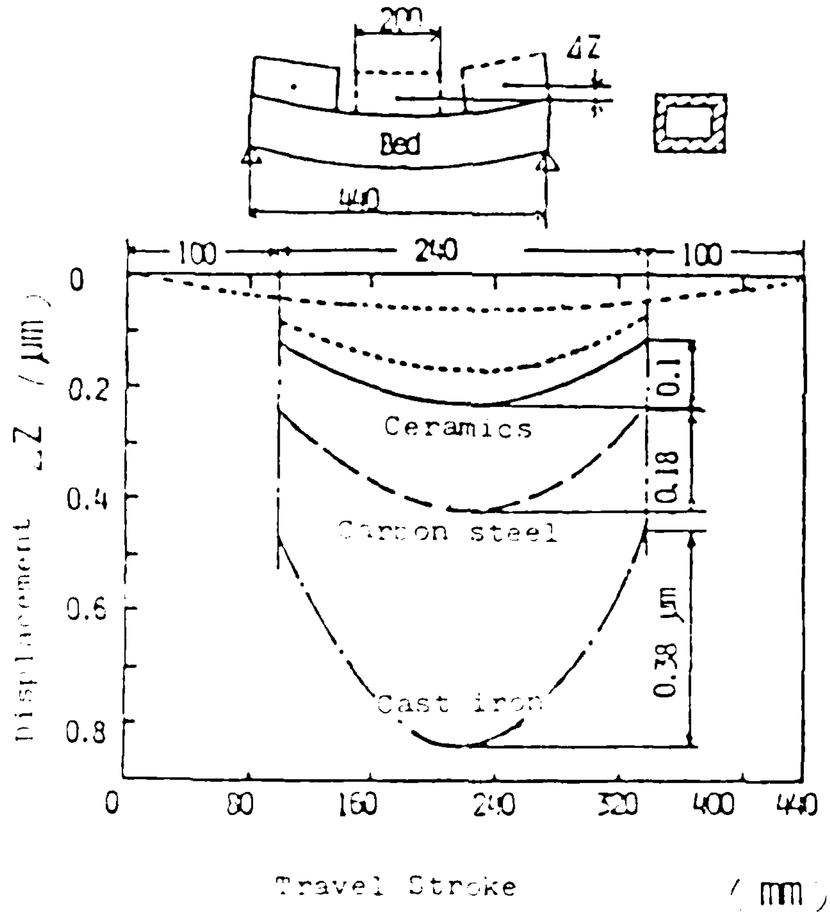
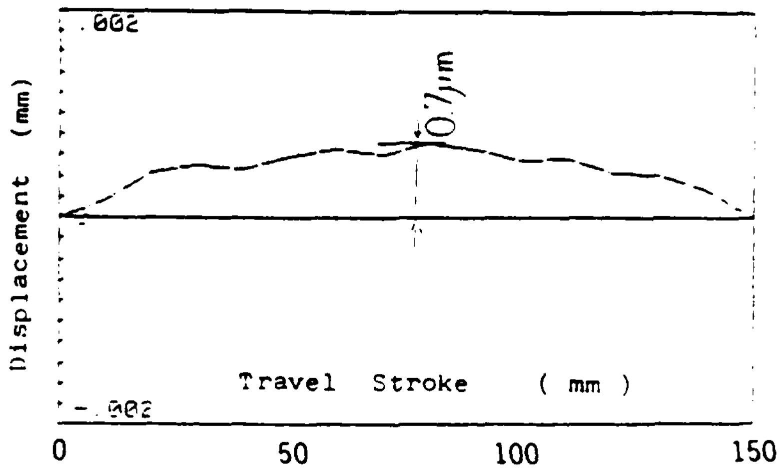
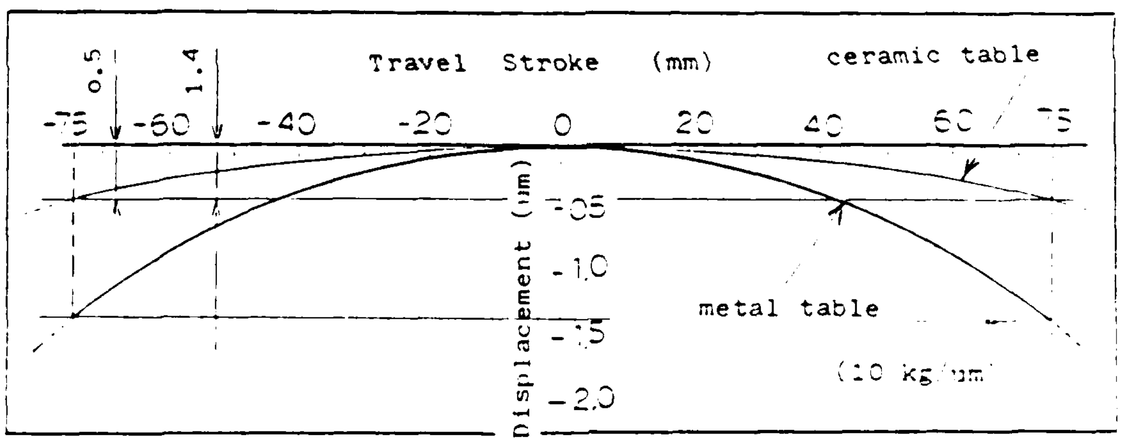


Figure 29. Comparison of displacement between ceramics and other materials.



(a) Measured value by laser measuring system.



(b) Calculated value (weight of ceramic table = 13 kg, metal = 30 kg).

Figure 30. Vertical straightness of upper axis of X-Y table.

Figure 31 shows transverse strength as a function of percent alumina for three processing techniques and for glass with higher thermal expansion. Fracture toughness for the same materials is shown in Figure 32.

Results obtained for the cordierite-mullite-glass composites are shown in Figures 33 through 36. Wachtman concluded that with the proper choice of glass and an optimum weight percent, excellent strengths can be achieved with glass-alumina composites, and three-component particulate composites offer an opportunity to achieve a wide range in properties.

Question:

Don't you think the microstructures of your material are important?

Answer:

Yes indeed, that is a principal point of the paper. The difference in the three alumina glass mixtures gives very large differences in strength. These are certainly structural/microstructural differences; they are not just compositional matters, since the bulk compositions are identical in these cases. Controlling porosity and other features of microstructures is very critical.

Question:

You mentioned dielectric constants. I have the impression you want to use these materials for substrate applications. Do you think they are strong enough for this use?

Answer:

The numbers that makers of electronic substrates usually quote to me as being desirable are about 40 ksi. These materials had at best 35 ksi in their present form. However, as I pointed out, these materials have not undergone prereaction to remove the porosity. If it is possible to improve strength in the same way in a three-component material as in alumina material, then I think they would be strong enough. They are marginal in their present form.

Wurm

Dr. Wurm described European-sponsored research in technical ceramics. Project areas and funding levels were described for intramural research at the Joint Research Centre, Petten, for contract research involving matching fiscal support by contractors, and for the coordinated so-called transfrontier research among the member nations. Since 1976, the European Economic Commission (EEC) has conducted high temperature materials research at the Joint Research Centre Establishment in Petten, Netherlands. Consequently, the Petten Laboratory has become an established center for high temperature materials testing, such as creep, fatigue, and corrosion. Up to 1984, the program focused on metallic systems, but now there is a 3-year program (1984-1987) on engineering ceramics. The primary objectives of this project are to clarify the mechanisms of deterioration and to develop guidelines for material improvements. This includes an effort to establish the interdependence between processing parameters, microstructure, and mechanical and thermal properties. The project involves about a 12-man effort, and the 3-year period is funded at about 2.7 million European Currency Units (MECU) (not including salaries).

The Commission also has a 3-year program (1983-1986) to reduce dependence on raw materials. This involves research in all member states in advanced refractories, silicon nitrides, carbides, zirconia, alumina, dispersion-strengthened and fiber-strengthened composites, as well as the study of wear, nondestructive testing, and evaluation of components for diesel engines. This raw materials program amounts to 9 MECU over the 3-year period, with contractors contributing 50 percent of the cost. The follow-on program, 1986-1989, is expected to be launched at about a 70-MECU level for a 4-year period. Roughly 30 percent of the budget will be devoted to advanced ceramics. Dr. Wurm provided a listing of proposed topic areas.

Another program discussed by Dr. Wurm was the BRITE project (Basic Research in Industrial Technologies for Europe). In 1983, hundreds of companies were surveyed by the European Economic Commission. Nearly 700 topics were suggested, and from these 9 technological areas were chosen to form the BRITE program. The program started in 1985 and 95 projects were initiated; 7 of the projects, in 4 of the program priority areas, were concerned with advanced ceramics research and development. These are all medium to large projects involving several industrial partners in efforts lasting up to 4 years. The total funding for the current 95 projects is 120 MECU, with 50 percent of the cost shared by the industrial partners. About 7 percent of the effort is devoted to high technology ceramics. Dr. Wurm also mentioned that about 10 projects of the so-called COST program involved ceramic materials and EUREKA activities on fiber-reinforced ceramics for diesel engine applications.

Question:

Can you explain compacting high performance materials?

Answer:

These efforts are for composite materials and components. Here we have the problem of the behavior of the fiber in the matrix. We need to know how the fiber is behaving, the orientation, and so forth. Then we can estimate the properties of the component. We have not yet seen many publications in this area. It is my personal belief that if we are going to have ceramics in engines, it will be composites. So we have to improve the properties of composites. Industry is waiting for such results before they can undertake reliable ceramic production.

Question:

Is your main point understanding the material, or is it finding applications?

Answer:

It is both. We need basic understanding and we need applications.

Question:

You said earlier that there was a project to produce sialon from coal. I think this is related to cinder ash. Are you going to be using cinder ash? Are you going to be using the cinder ash alumina and silica? How are you going to get sialon from coal? What is the application of this sialon that is going to be produced from coal?

Answer:

The purpose of this research is to find cheaper ways of producing sialon. Sialon is still quite expensive and we want to start with the cheaper raw materials. It can be done in many ways, but I'm not going to describe the methods now. The published work will be available in the spring of 1987.

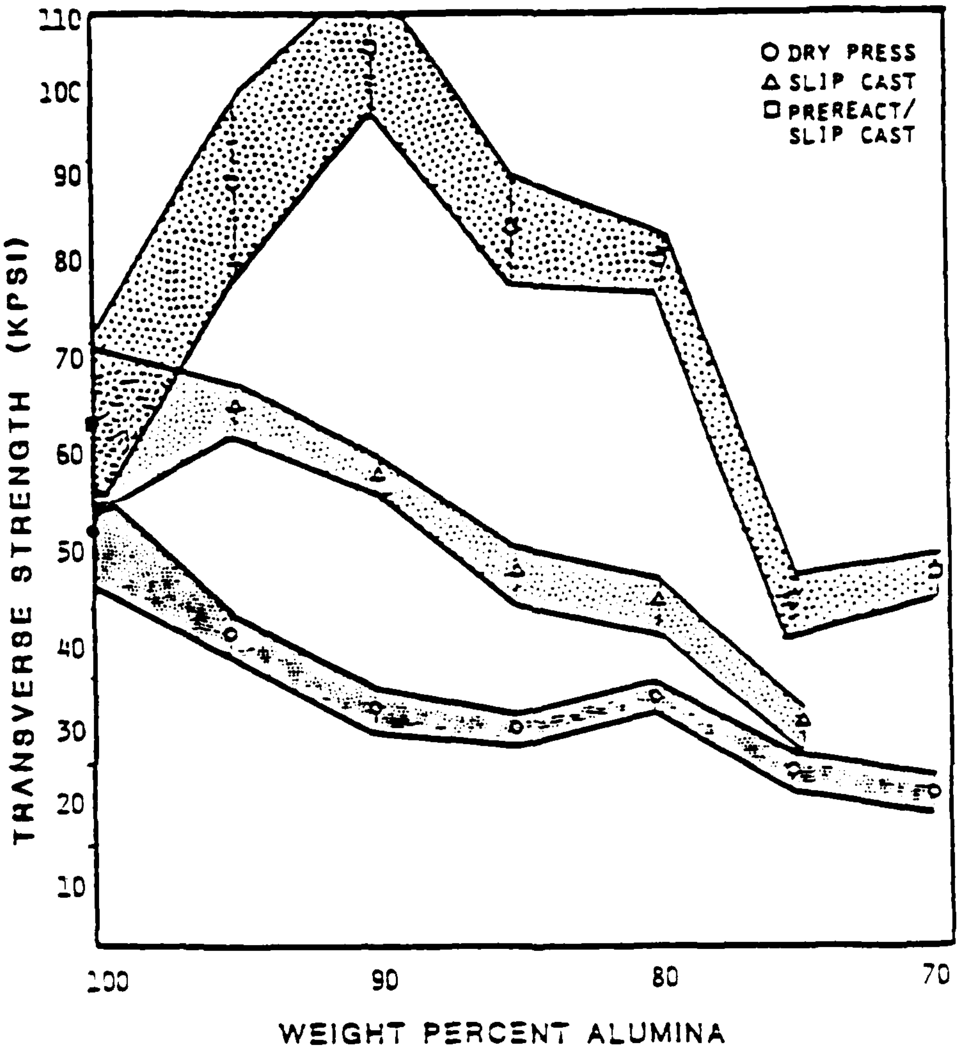


Figure 31. Transverse strength of alumina-glass composites.

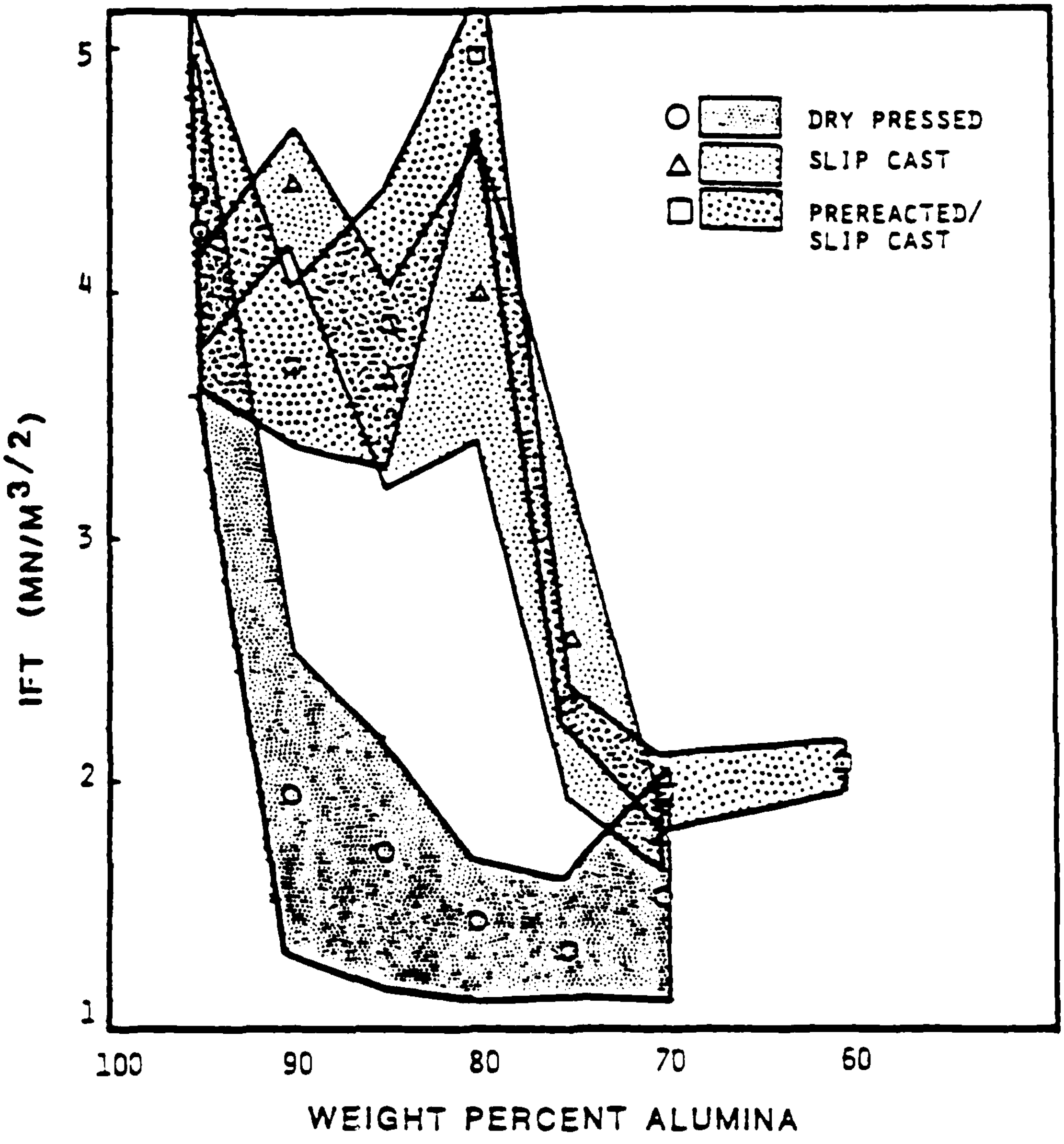


Figure 32. Fracture toughness of alumina-glass composites.

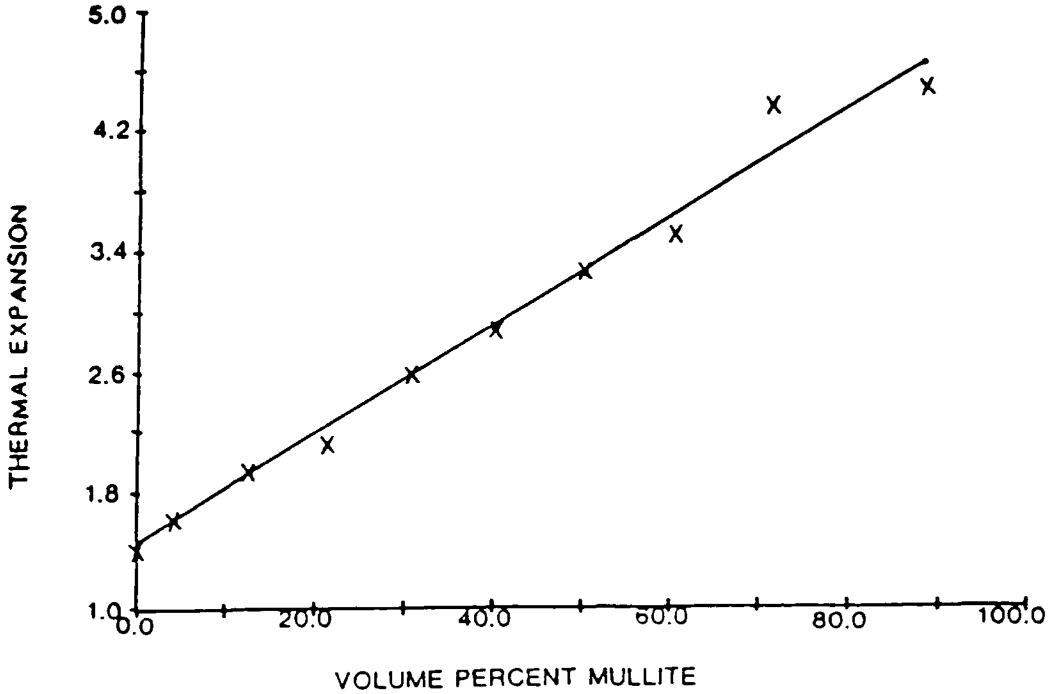


Figure 33. Thermal expansion of mullite-cordierite composites.

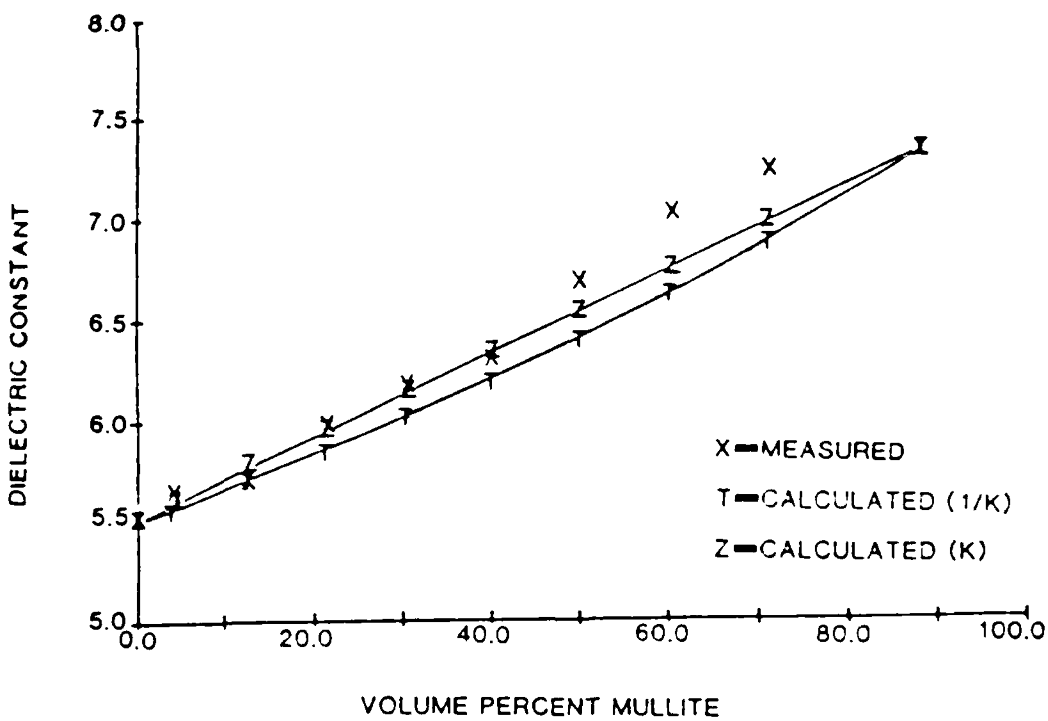


Figure 34. Measured and calculated dielectric constants.

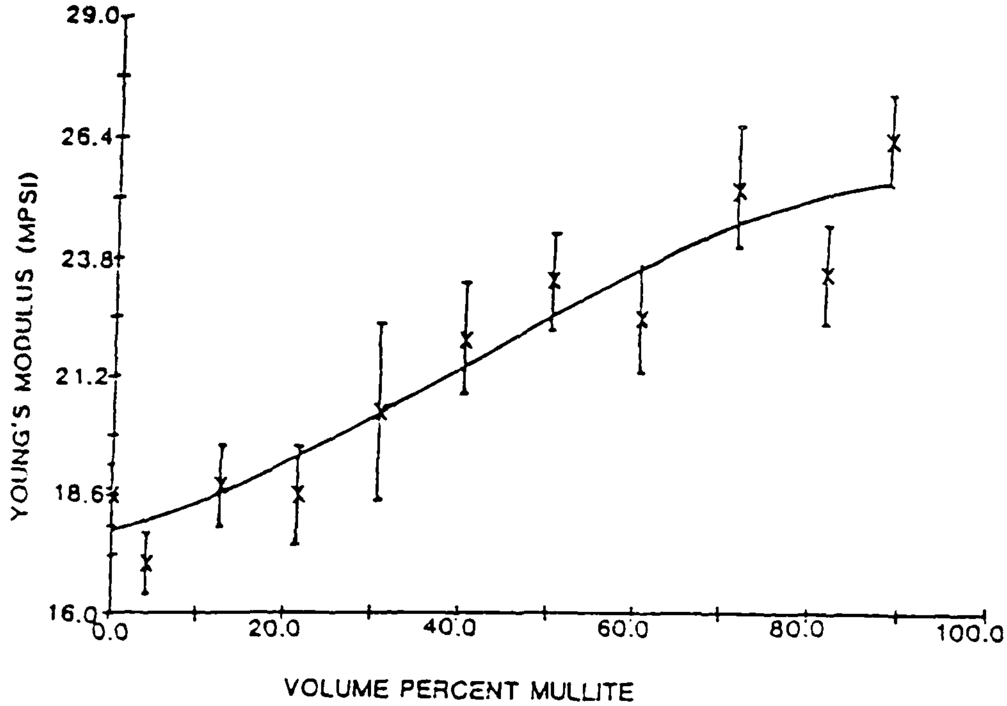


Figure 35. Young's modulus of mullite-cordierite composites.

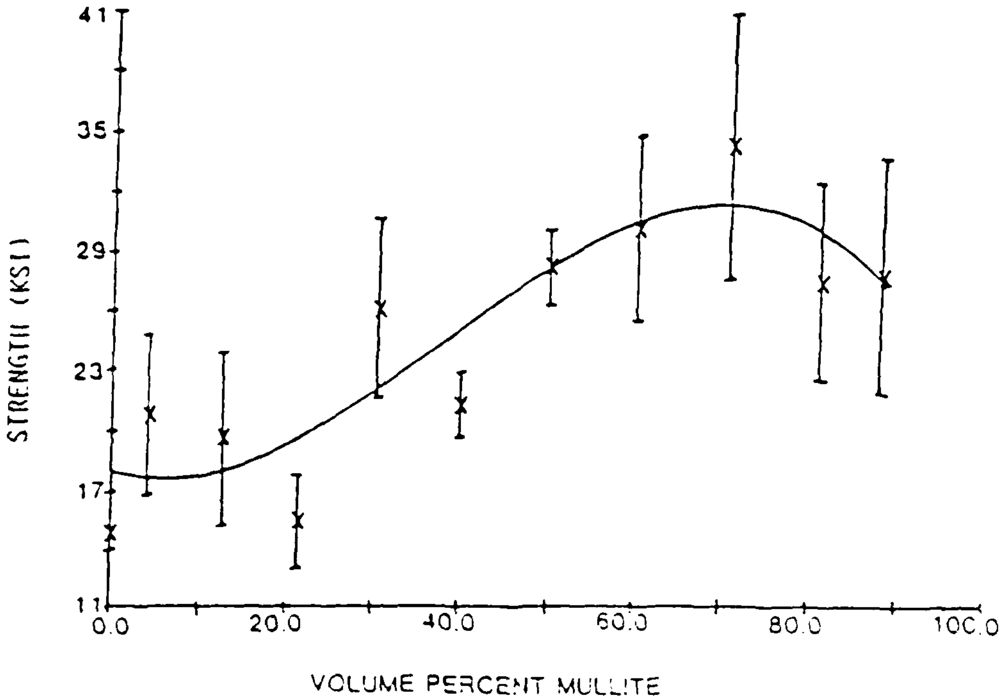


Figure 36. Strength of mullite-cordierite composites.

CHAIRMEN SUMMARY COMMENTS

Dr. Hamano

The first three papers in this session dealt with some of the unique applications of structural ceramics, i.e., large blower fan applications, large-size heat exchangers, and the application of ceramics to air-sliding mechanisms. All of these were from different industrial segments and dealt with some very specific features of ceramics for such applications.

There are many everyday items, such as golf putters, scissors, knives, and others, made of fine ceramics. These everyday items have helped the average person to understand some of the features of fine ceramics and have drawn people's attention to the technology of fine ceramics. The applications presented by the industrial representatives, however, are typical samples of very sophisticated use of fine ceramics in industry and are more important to us.

In the United States and perhaps in some European countries, the development of fine ceramics technology is supported mainly by the government. In Japan, however, it is mainly the industries that provide the financial support. Industry needs more immediate "fruits" from research and development (R&D). These examples of applications are the fruits needed. I'd like to emphasize the importance of R&D fruits to encourage R&D activities.

Many people are interested and involved in the development of very sophisticated applications of fine ceramics, such as ceramic gas turbines. This is a very important R&D subject that has great influence in the development of ceramic technologies. But for people who carry on such R&D at the risk of their companies, the increasing expense is creating added stress. It is not only necessary to have expensive manufacturing facilities, but we also need expensive testing facilities. Design tools are very expensive and very indispensable. So 5 years or maybe 10 years from now, will it really pay off to carry out such work? I think this is a very straightforward and nagging question that we all have in mind. Does it really pay?

I hope we can continue to research and develop fine ceramic technologies, encouraged by immediate fruits, and set our goal at more sophisticated fruits, such as gas turbines. I am sure that such workshops like this will help us bear useful fruits. We would like to continue to give our full support to these workshops and promise you our participation. We in Japan would like to know about the situation in other parts of the world.

Dr. Larker

Professor Wachtman discussed a novel product, with a lower dielectric constant than alumina, that could fulfill the function as substrates for microcircuits. This is the way of the future in the ceramics area--to find alloys, combinations, particulates, and fiber and whisker composites.

Dr. Wurm gave us an overview of the European Communities sponsored research in ceramics. It was good to see that such areas as joining and composites took a rather important part in this program.

CONCLUSION

This first workshop proved to be reasonably informative and the committee members decided to continue with at least two more or perhaps three additional meetings as follows:

FUTURE WORKSHOPS

Workshop Number 2

Characterization of Ceramics and Development of International Standards

9–11 March 1987, Nagoya, Japan

The purpose of this workshop is to document the status of characterization techniques currently being applied to advanced ceramics and to explore possible advance techniques. In addition, the wide ranging international round-robin testing activities currently underway will be reviewed; quality assurance procedures and nondestructive evaluation approaches will be described. Current activities in developing international standards will be surveyed and evaluated.

Workshop Number 3

Status of Centers of Excellence for Advanced Materials

September 1987, Tokyo, Japan

The purpose of this workshop is to document the range of activity at government, industry, and particularly at university centers of excellence. It is difficult to determine educational and research opportunities that exist in the international community. Many industrial organizations as well as graduate students and senior researchers are interested in such a data base. In addition to educational activities, major accomplishments and program emphasis and thrusts will be presented. The possibilities for research assignments and cooperative projects will be described. Problems as well as opportunities in international education will be described from the foreign student perspective.

Workshop Number 4

Advances in Materials, Processing, and Manufacturing Science

March 1988, Nagoya, Japan

This workshop will report on the most recent accomplishments in ceramic materials technology and discuss potentials for new and improved materials and components for high performance applications. The sessions will provide an excellent overview of major research activities and a comprehensive forecast of potential limits and new frontiers of materials capabilities.

Edward Mark Lenoe is on leave from the Army Materials and Mechanics Research Center and will be on assignment with ONRFE/AFOSRFE for 2 years, having joined the staff in October 1985. Previously he managed the AMMRC Reliability Mechanics and Standardization Division, served as operating agent for the International Energy Agency implementing agreements on high temperature ceramics for heat engine applications, and also managed numerous major contracts. His initial studies for ONR will be devoted to structural ceramics.

POSTECH: KOREA'S NEW RESEARCH-ORIENTED UNIVERSITY

Justin H. McCarthy

On 3 December 1986, the Pohang Institute of Science and Technology (POSTECH) was officially dedicated in Pohang on the southeast coast of Korea. The composition and purpose of POSTECH are described in the context of Korea's recent tremendous industrial growth and its commitment to development of a national infrastructure for the advancement of science and technology in Korea.

PROLOGUE

In late November 1986, I travelled from Japan to Korea to visit eight of the principal academic, research, and industrial activities (see Appendix) that in one way or another are responsible for Korea's remarkable rise as a world-class shipbuilding nation. What I discovered was much more, a nation of very proud and dedicated people looking to the future in many directions, people who in the words of Tae Joon Park are determined "... to lay the foundation for autonomy and independence in science and technology [so that Korean industry can] make the leap needed to join the rank and file of the advanced nations who are fiercely competing for industrial leadership in the Twenty-First Century." Time and time again I was impressed deeply by the commitment and zeal of individuals to contribute to Korea's development. In some cases very successful scientists and engineers I had known in the United States had returned to Korea to receive less than half their former pay for six and even seven 12-hour workdays each week.

In fact, I learned at the Ministry of Science and Technology in Seoul that shipbuilding, when considered as a subset of the mechanical sciences, now ranks third in Korea's national development priorities behind electronics and chemistry. Korea's share of world shipbuilding has grown from about 8 percent in 1984 to about 20 percent in 1986 and is expected to exceed 30 percent in the near future. Principal emphasis is currently on establishing Korean manufacturing capability for all shipboard materials and equipment, significant portions of which are still imported, largely from Japan, at a time when the yen is very high relative to the dollar, and development of sophisticated in-house design and research expertise. However, shipbuilding is a labor-intensive industry. As wages increase, other developing nations eventually will enter the international market, and shipbuilding along with other heavy industries in Korea will be forced to contract, as is currently happening in Japan, and as happened many years ago in the United States. Because this is viewed as a long-term pattern, high-tech industries are being vigorously promoted in Korea for the future.

Up until the present time, nearly all of Korea's needs for graduate education in science and engineering have been satisfied by sending students to universities primarily in the United States, but also to Europe and Japan. Large numbers of these students are now returning home, rather than staying in their host countries as many formerly did, and they are finding employment in government institutes, universities, and in newly organized "research departments" of Korean industrial plants. In most cases the research is of a very applied nature, involving adaptations of western or Japanese technology and equipment. In time the young researchers with whom I spoke should be able to identify and pursue original and fundamental approaches to engineering and scientific problems, and, with careful tending, the kind of in-depth infrastructure known in the United States and Japan will be established, spanning the gamut from junior to senior scientists.

To help make this dream a reality, a major new research-oriented university has recently been established in Korea, and it will be the subject of the remainder of this article. Some have compared it in concept to the California Institute of Technology (CALTECH) in the United States, others to the Weizmann Institute in Israel.

POSTECH

On 3 December 1986, the Pohang Institute of Science and Technology (POSTECH) was formally dedicated in ceremonies opening Korea's first independent research-oriented university with both graduate and undergraduate degree programs in science and engineering. POSTECH was conceived in 1984 by Tae Joon Park, chairman of Pohang Iron and Steel Co., Ltd. (POSCO), the world's largest steel manufacturing complex, located within view of POSTECH in the southeastern port city of Pohang on the Sea of Japan. A steel-related research laboratory established by POSCO in 1978 has been reorganized and expanded to become the Research Institute of Scientific Technology (RIST) and is located side-by-side with POSTECH on a 350-acre campus in order to promote faculty and student participation in joint investigations with RIST research staffers. The total construction cost of $48 million was paid by POSCO and the campus was largely completed within a very short 15 months (Figure 1). In addition, as a result of their very profitable international marketing, POSCO expects to provide POSTECH with an endowment fund of $200 million over the next 5 years.

Creation of POSTECH establishes Pohang as the third major research and education center in Korea for science and advanced technology, the other

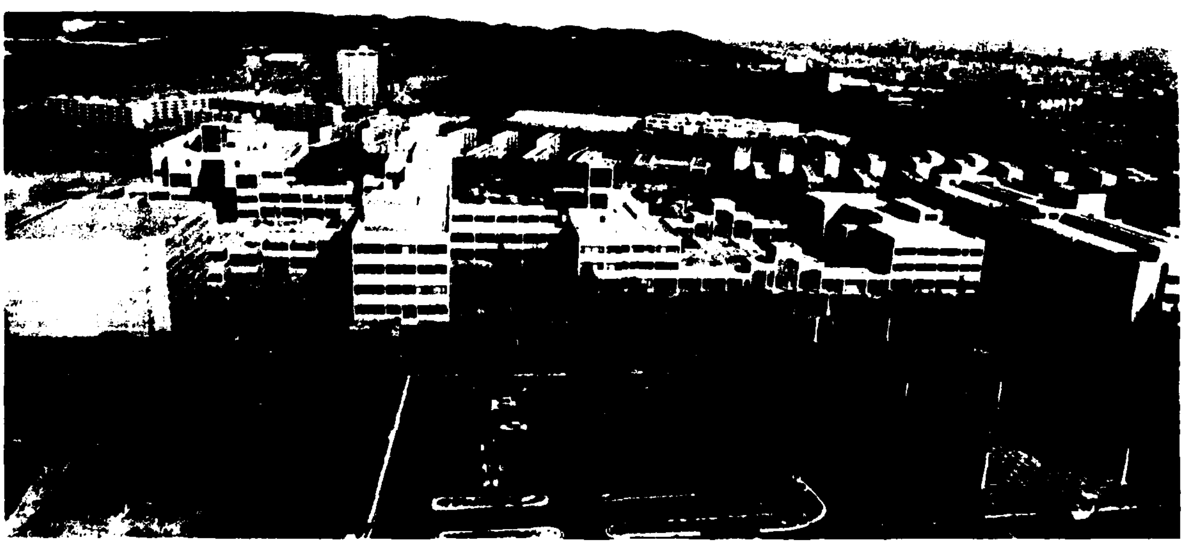


Figure 1. Aerial photo of POSTECH and RIST buildings in foreground, with housing behind and POSCO steel plant on the distant right.

centers being located in Seoul and Taejun. Seoul is the home of Korea's most prestigious university, Seoul National University (SNU), and the Korea Advanced Institute of Science and Technology (KAIST). SNU is primarily an educational institution. KAIST, like POSTECH, combines both research and education but offers only graduate degrees. It resulted from a marriage in 1981 of two government institutes: the Korea Institute of Science and Technology (KIST), a Battelle-type research laboratory founded in 1966, and the Korea Advanced Institute of Science (KAIS), a graduate school founded in 1971. It is currently planned that KAIST will be moved in 1989 to the Daeduk Science Town near Taejun where it will be in company with another first-rank national research-only center, the Korea Institute of Machinery and Metals (KIMM).

During my visit to POSTECH I met with its ebullient prime mover, President Hogil Kim, and his Vice President and chairman of the Mechanical Engineering Department, Dr. Choung Mook Lee. Dr. Kim was formerly Professor of Physics at the University of Maryland and was well known for his research on particle and plasma physics. Dr. Lee was formerly a prominent research hydrodynamicist and colleague of mine at David Taylor Naval Ship Research and Development Center and, before his return to Korea, a scientific officer at the Office of Naval Research in Washington. Dr. Kim has spent much effort over the past 2 years successfully recruiting Korean-born scientists in the United States for faculty positions at POSTECH. About 80 percent of the 52 faculty members appointed to date have received their Ph.D. degrees from American universities, with about half of the remainder receiving their Ph.D. degrees in Korea from KAIST. In keeping with the emphasis on research at POSTECH, many of the faculty members have research rather than teaching backgrounds. In recruiting overseas Koreans it has been easier to obtain senior and junior personnel, and special efforts are now being made to obtain middle-level faculty members. These are typically people in their 30s and 40s whose wives and children are reluctant to change their lives in midstream.

Why are researchers and academics returning to Korea from the United States? According to President Kim and others, there are a number of reasons. First, research funding has become more difficult to obtain in the U.S. Funding for basic research at Korean universities has increased tenfold in 3 years. Second, most Koreans feel they owe a special debt to their birthplace, so for "patriotic" reasons they are motivated to return for longer or shorter periods of time, in spite of the longer working hours and significantly reduced pay. Related to this is a collective desire to establish a Korean start-to-finish research and development (R&D) capability because of the difficulty of directly transferring technology to Korea from the U.S. or elsewhere. Finally, the steep positive gradient of prosperity, which was obvious everywhere after 10 years away from Korea, surely encourages educated people to return.

Because POSTECH is new and well removed from Seoul, the cultural and political center of Korea, extra benefits are given to new faculty members. These include free apartment rentals, recreational and schooling facilities shared with POSCO employees, payment of children's university tuition in Korea, sabbatical leaves, attractive retirement plans for senior faculty, and a free new Excel auto manufactured by Hyundai Heavy Industries in nearby Ulsan.

In March 1987 POSTECH admitted its first undergraduate class of about 240 freshman in nine departments: physics; chemistry; mathematics; computer science; metallurgy and material science; and chemical, mechanical, electrical and electronics, and industrial engineering. The graduate programs will be inaugurated in March 1988 with 135 students and a total POSTECH faculty of about 120 members. When all development plans are implemented in several years, there will be 11 departments with 300 faculty members, and the number of undergraduate and graduate students will grow to about 1,500 and 1,000, respectively. Many of the faculty will be conducting joint investigations with RIST researchers whose number is expected to grow to 600.

Dr. Kim believes that the metallurgy and material science department will, at least initially, be the strongest group at POSTECH. Part of this is no doubt due to the excellent equipment and personnel resulting from POSCO's earlier research efforts. Major research projects for the future will emphasize robotics and plans are being laid for POSTECH to build its own supercomputer over a period of 5 years. A VAX 8800, one of the most powerful computers in Korea, is already operating at POSTECH. Because of his own research interests, Hogil Kim also hopes one day to acquire a particle accelerator for POSTECH. A wind tunnel is planned for fluid mechanics research and a three-component laser Doppler velocimeter will be acquired soon. The library is starting with 45,000 books and subscriptions to 560 journals, with microfiche copies of back issues. The goal is 5,000 journal subscriptions within 10 years.

As a result of widespread national publicity about POSTECH in the mass media, POSTECH has been successful in attracting very bright high school graduates in its first freshman class. All of them scored within the top 2 percent in the Korean Scholastic Aptitude Test. Early establishment of exchange student and professor programs with institutions in the United States, England, Germany, and France is of great importance to POSTECH administrators. Sister relationships have been arranged with a number of colleges and universities abroad. Visiting faculty and scientists will be welcomed beginning in 1988.

CLOSING REMARKS

The relative prosperity of Korea today has been achieved through its heavy industries, largely through its steel industry. There can be no doubt that Koreans are determined to continue to succeed and that they are working together "like molten iron" to produce advanced products. Much of the technology has been borrowed from other industrialized countries. Looking forward to the 21st century, the framework is now being put in place to achieve a much greater self-sufficiency in Korea with regard to scientific and technological innovation and advancement. POSTECH is one of the new key players established to help achieve this goal. If external military forces and internal political crises can be resolved, I expect that Korea will be eminently successful in achieving its goal.

Justin H. McCarthy is on leave from the David Taylor Naval Ship Research and Development Center, where he was head of the Naval Hydromechanics Division, and will be on assignment with ONRFE/AFOSRFE/AROFE for the next year, having joined the staff in September 1986. He was also the Technical Manager of the Navy's Propulsor Exploratory Development Program. His professional interests include propulsor hydrodynamics, drag reduction, and computational fluid mechanics. Mr. McCarthy is a member of the Advanced Planning Committee of the Society of Naval Architects and Marine Engineers, an Associate Editor of the Journal of Ship Research, and recently served for 6 years as Chairman of the Resistance Committee of the International Towing Tank Conference.

Appendix

ITINERARY IN KOREA

26 Nov	R&D Coordination Office, Ministry of Science and Technology, Seoul
27 Nov	Dept. of Naval Architecture, Seoul National University, Seoul
28 Nov	Ship Research Station, Korea Institute of Machinery & Metals, Daeduk
30 Nov	Pohang Institute of Science and Technology, Pohang
1 Dec	Maritime Research Institute, Hyundai Heavy Industries Co., Ltd., Ulsan
2 Dec	Technology & Development Division, Daewoo Shipbuilding and Heavy Machinery Ltd., Geoji-kun
3 Dec	Agency for Defense Development, Chinhae
4 Dec	Dept. of Mechanical Engineering, Korea Advanced Institute of Science and Technology, Seoul

SYMPOSIUM ON TURBULENCE MANAGEMENT AND RELAMINARIZATION

Justin H. McCarthy

An international symposium on the physics and control of transitional and turbulent flow processes was held in Bangalore, India, from 19-23 January 1987. From the many excellent presentations it was clear that significant progress is being made in unraveling some of the most difficult problems of fluid mechanics.

INTRODUCTION

An International Union of Theoretical and Applied Mechanics (IUTAM) Symposium on Turbulence Management and Relaminarization was held in Bangalore, India, from 19-23 January 1987. The symposium was cochaired by Professor R. Narasimha, Director of India's National Aeronautical Laboratory (NAL), and Professor Hans Liepman of the California Institute of Technology (CALTECH). The hosting organizations were NAL and the Indian Institute of Science (IISc), the venue for the meeting. The objective of the symposium was to bring together researchers to discuss the physics of transitional and turbulent flow processes and techniques that are under development for actively or passively controlling the flows. These topics are of major interest to the U.S. Navy because delay of transition from laminar to turbulent flow and turbulence management can lead to significant reductions of both frictional drag and flow noise.

About 70 people attended the symposium, with India and the United States each providing about 30 participants. The remaining attendees were from Australia, FRG, Japan, the U.K., and the U.S.S.R. The symposium consisted of 3 invited talks, 36 papers, and 1 panel discussion that focused loosely on issues raised in the papers and talks. Two of the papers were not presented because the authors were absent. Abstracts of the papers were distributed at the meeting and the final papers will be available when the proceedings are published in about 1 year.

Most of the symposium papers were given by American authors, several with Indian coauthors, reflecting the breadth and depth of experimental, theoretical, and numerical research on flow physics and control in the U.S. It was clear from the summary-type contributions of Levchenko and Kozlov that, although not visible at the symposium, research on flow control in the U.S.S.R. is also proceeding on a very wide front.

For purposes of organization, most of the papers can be divided into two broad groups: (1) papers dealing with boundary layer flows and (2) papers dealing with jets. These groups may be further subdivided according to whether the flow is laminar, transitional, or turbulent and according to the type of flow management or manipulation that was introduced. For boundary layer flows, which were the subject of the vast majority of the papers, at least 10 types of manipulation were covered (parentheses give numbers of papers): large eddy breakup devices (6), riblets (5), compliant coatings (3), local heating (3), vibrating ribbons or pins (2), local geometry (2), suction (1), sound waves (1), polymer additives (1), and deceleration (1). Types of manipulation reported with jets involved nozzle geometry (2), time-dependent mass flow (2), sound waves (2), and an oscillating flap (1).

As stressed by many of the participants throughout the course of the symposium, turbulence management in boundary layer flows should not be viewed solely from the standpoint of its potential for reduction of drag or noise. Manipulation techniques should also be thought of as research tools for creating new flow structures which, when carefully measured and analyzed, lead to improved knowledge and understanding of the underlying physics of transition and turbulent flow processes. To paraphrase Corke (Illinois Institute of Technology), who stated it so well in summarizing his own excellent paper on boundary layer transition:

> [Experiments should use] a method for rigorous sensitivity testing of key parameters governing the early development and growth of three-dimensionality in unstable boundary layers. It [should allow] the control of essential features of the disturbance environment which otherwise are hardly even adequately known and exercise critical influence on nonunique nonlinear developments. [It should provide] a systematic approach to search for basic mechanisms governing transition and breakdown.

For me, the high points of the symposium were contained in five of the papers and in the manipulated, but uncontrolled, panel discussion. In the following I will review these five papers and attempt to give some of the flavor of the panel discussion. At the end I will give brief summaries of most, but not all, of the remaining papers, and finally some conclusions.

FULL NUMERICAL SIMULATION OF NATURAL TRANSITION

For the first time anywhere, Reed (Arizona State University) and Yang and Ferziger (Stanford University) have successfully achieved full numerical simulation of a *natural* transition process. They used the full time-dependent Navier-Stokes equations for parallel flow over a decelerating flat plate to model the boundary-value problem experimentally studied by Gad-el-Hak. The initial state is a laminar Blasius boundary layer having low-amplitude three-dimensional random noise, and as observed experimentally, the temporal transition process is assumed periodic in space. The computations show inflected velocity profiles and strong instability waves due to deceleration, initiation of secondary instabilities, hairpin vortices, and breakdown. Excellent correlation was shown with the experimental data. This work should pave the way for other successful numerical simulations.

MANAGED INTERACTIONS BETWEEN PLANE AND OBLIQUE WAVES

Corke (Illinois Institute of Technology) presented a very important paper on the use of a spanwise array of heaters, suspended above the wall of a flat plate, which permitted simultaneous generation of two-dimensional (2-D) Tollmien-Schlichting (T-S) waves and pairs of three-dimensional (3-D) oblique waves so as to systematically control the nonlinear evolution and breakdown of laminar flow. From careful analysis of smoke-wire traces and phase-conditioned hot-wire surveys of all three velocities at prescribed locations in space, he elegantly documents the resonant growth of energy in subharmonic (oblique) modes and the formation and breakdown of staggered streamwise vortex patterns into turbulence. A broad range of controlled conditions was investigated, only a few of which could be sampled in the paper. Corke's experiments provide direct support for the earlier theoretical/numerical predictions of Craik (1971) and Herbert (1983) concerning the exponential growth of energy in the oblique modes through interaction with the plane T-S waves.

SHARK SKINS AND DRAG REDUCTION

Dinkelacker (Max Planck Institute, Göttingen) gave a fascinating paper on surface features of fast-swimming sharks that may be related to drag reduction. The features include cellular regions of roughly longitudinal ridges having nonuniform sharp peaks and broad valleys and "pit organs" that he speculated served as pressure transducers in a feedback loop that led the skin to cause small- rather than large-scale turbulent bursting. He further described a different orientation of ridges in flow stagnation regions and differences between slow and fast swimming sharks, about 40 species in all. Experiments he conducted in pipes with sharklike grooves resulted in drag reductions of up to 3 percent at Reynolds numbers (based on pipe diameter) between 8,000 and 45,000. At higher Reynolds numbers, the grooves produced higher drag.

TWO PAPERS ON VORTEX PAIRING AND MIXING IN JETS

In a very well-organized and stimulating talk, Hussain (University of Houston) broadly reviewed active and passive methods for jet control, the former involving sinusoidal excitation at selected frequencies and the latter using collars or modification of jet cross section by changes in nozzle geometry. Most of his presentation focused on the fascinating mechanics and topology of elliptic jets, which he believes are useful generic configurations intermediate between circular and plane jets. Because elliptical vortex filaments have nonuniform spanwise curvature, they are inherently unstable and three dimensional. Self-induction causes the major axis to shrink and the minor axis to grow, causing fluid to be ejected outward from the jet axis along the initial minor axis, thereby providing a mechanism for catastrophic mixing not found in circular or plane jets. Hussain described his research on the very different vortex pairing and coherent structures of elliptic jets of moderate aspect ratios. He found that acoustic excitations, when properly tuned, increased jet turbulence levels (up to 200 percent) and cross-sectional area much more than is possible for circular jets. Conversely, he showed evidence that excitation could also produce 40-percent reductions of jet turbulence. As in other papers, careful manipulation of the coherent vortex structures through geometry or excitation was identified as the key to flow control.

In a second very fundamental and important theoretical and experimental contribution, Wyganski (University of Arizona) reported on vortex pairing processes and mixing in a plane turbulent jet that was excited by a small flap oscillated at one (F) or two (F and F/2) frequencies in the jet. From velocity and streakline data, he found that lines of maximum vorticity gradient correlated with turbulent pairing of streaklines and determined that vortex pairing and rollup occur concurrently. Because nonlinearities were weak, Wyganski was able to use an inviscid linear stability theory, accounting for mean flow divergence in the jet, to reproduce measured streakline patterns and vortex pairing by linear superposition of flap-induced disturbance modes. Wyganski, in agreement with Hussain, stressed again and again the crucial importance of the vorticity field and pairing. In fact, without vortex pairing he asserted that mixing and the creation of turbulence would stop.

THE PANEL DISCUSSION

A panel discussion took place at the end of the afternoon of the next to the last day of the meeting and dealt in a rather random but refreshing manner with issues raised at the symposium up to that point. It began with brief, general opening statements by Saaric (Arizona State University), Yajnik (NAL), Wyganski (University of Arizona), and Reischman (Office of Naval Research (ONR)). Saaric drew a whimsical Venn diagram showing the solution of turbulence control to be the vanishingly small region of intersection of theory, numerics, and experiment. Yajnik said clear thinking was the key and urged participants to read Poincaré's work on nonlinear dynamical systems. Wyganski, speaking of free shear flows, asserted that Reynolds time-averaged equations don't lead far and that understanding coherent structures and vorticity was the key to control. Reischman, speaking as a program manager, stressed the importance of interdisciplinary approaches and the importance of "transduction" science in achieving flow control.

The leader of the panel discussion then posed a lengthy series of questions, addressed one-by-one from the floor, in order to determine whether a consensus existed on any of the important issues. In an abbreviated sampling, the questions and answers went something like the following paraphrased account.

- *Do wave cancellation methods have promise?*

Saaric: No; at least not near term.

Sengupta: Yes; 3-D waves are related to 2-D waves.

Saaric: No; 3-D waves reappear after 2-D waves are killed.

Liepman: It's too early to decide. Work on the 3-D problem has just begun. Even 2-D cancellation is worthwhile.

Levchenko: Agree with Saaric; 3-D explosion eventually occurs.

Pfenninger: Spanwise instabilities are important.

- *Are active control methods useful?*

Robey: Yes, at least for 2-D flow instabilities; 3-D control may be computationally too intensive.

Levchenko: Saaric and Liepman are both correct; it may be practical to use control devices far downstream.

Wyganski: Why not introduce trains of plane and oblique waves and then remove them in order to improve chances of cancellation?

Liepman: Doing these things will be very complex in supersonic and hypersonic flows.

Nagib: Computers may improve tremendously, making control possible.

- *Are passive control methods useful?*

No comments, probably due to audience fatigue.

- *Do riblets give drag reduction?*

Consensus: Four to 8 percent looks okay.

- ***Do large eddy breakup devices (LEBUs) give drag reduction?***

  Savill: Yes, on aircraft.

  Wilkinson: Yes, on aircraft, if strut drag is low.

  Nagib: Skin friction is always reduced; 10 to 15 percent is best net drag reduction in the laboratory. Skeptical about practical applications.

  Narasimha: LEBU may be different in channel and boundary layer flows.

  Saaric: Will LEBU work at high Reynolds numbers in flight, where the turbulence structure may be different than in the laboratory?

  Nagib: LEBU is an important tool for studying flow control.

BOUNDARY LAYER CONTROL

Research in Novosibirsk

In a paper and an invited talk, Levchenko and V.V. Kozlov (Institute of Theoretical and Applied Mechanics, Novosibirsk) gave reviews of recent Soviet research, largely their own work, on localized active transition control using vibrating ribbons, sound waves, and periodic suction or blowing. It was apparent that a very large body of carefully conducted experiments had been completed but that theories were still lacking. Like Corke, they found nonlinear processes to be very important in transition and a subharmonic theory based on resonant triads of T-S waves looked promising. They believe for active control of transition to work, low frequency disturbances should not be introduced and some minimal level of 3-D disturbance control must be introduced; stabilization of the flow can be achieved by damping of low frequency disturbances, but action on the principal instability waves is better. They, along with some other participants, saw no obstacles in principal to ultimate development of an electronics package to control natural transition processes. (But, recall Levchenko's comments during the panel discussion.) Such optimism may be justified for laboratory demonstrations. For field conditions at Reynolds numbers on the order of 10^9 to 10^{10} much more research is required.

LEBUs

The LEBU, a large eddy breakup device, consists of a stationary, thin slat parallel to a boundary. It interferes with the large eddy dynamics in the outer part of a turbulent boundary layer in such a way as to reduce wall shear stresses downstream of the device.

Nagib (Illinois Institute of Technology), in an invited paper, provided a very fundamental introduction to boundary layer properties and their manipulation by LEBUs. He discussed correlations of flat plate wall shear stress measurements at one location with measured values at another location of Reynolds stresses that exceeded some critical value. From extensive computer analyses of the data, he concluded the existence of roller vortices in the boundary layer that cause either fluid "injection" or "ejection" events that are associated with high or low values of wall shear stress. Nagib believes that these "rollers" are a key feature of turbulent boundary layers, but more work will be required to establish their connection with the hairpin vortices associated with turbulent bursting.

Bertelrud and Watson (National Aeronautics and Space Administration (NASA)) reviewed previous investigations of LEBUs in incompressible flow on flat plates which show that local skin friction reductions of 10 to

30 percent and net drag reductions as high as 20 percent can be obtained. They also discussed tests of swept wings under full-scale transonic flight conditions that indicated LEBU alteration of turbulence structure as far as 200 boundary layer thicknesses downstream of the device where skin friction levels had returned to baseline values. These data, together with boundary layer calculations, are being used to help identify the flow characteristics of "optimum" wing profiles for LEBU application. As pointed out by Narasimha (NAL), the potentially important effect of velocity gradient normal to the LEBU was neglected in the analysis.

Takagi (National Aerospace Laboratory, Japan) reported cases where LEBUs caused a net drag increase in flat plate flow, in disagreement with the work of other investigators. The lack of drag reduction was traced to the existence of two pairs of large vortices in the wind tunnel that created a spanwise 3-D flow, thereby rending the 2-D LEBUs ineffective.

Unlike flat plate flows, mounting data continue to raise doubts about LEBU drag reduction in channel or pipe flows. Kailas Nath et al. (IISc) reported no net drag reduction in channel flow, in agreement with recent measurements made in Japan and Switzerland. This may be related to the lack of intermittency in channel flows, as opposed to external boundary layer flows where net drag reductions of up to about 20 percent have been measured. Savill (Cambridge University) presented Reynolds stress measurements in channel flows with adverse pressure gradients but was unable to draw conclusions about LEBU drag reduction.

Finally, Yajnik et al. (NAL) proposed that the cumulative frictional drag reduction up to a distance x downstream of a device is inversely proportional to (x–c) with c a constant. While no theoretical or physical basis was given for the relation, he did show good correlation within a small sample of data.

Riblets

Riblets consist of small striations on a surface aligned in the flow direction. Unlike LEBUs, which interact with the outer region of a boundary layer, riblets interact with the inner region to produce drag reduction.

Choi (British Maritime Technology) described flat plate measurements of wall pressure fluctuations that were reduced by about 4 percent at frequencies below 10 Hertz for a certain V-groove riblet. (This contrasts with reductions of about 12 percent measured at NASA for LEBUs.) Choi found a correlation between the reduction of low frequency pressure fluctuations and a reduction of Reynolds stresses, and inferred the existence of "roller" vortices very close to the wall, which are associated with drag reduction. This interpretation is similar to that of Nagib, who found "rollers" *for LEBUs, albeit further from* the wall than for wall riblets. Wallace (University of Maryland) presented a very different view based on his measurements in riblet grooves. He found that riblets have a very subtle effect on turbulence structure and produce drag reduction entirely by viscous effects (i.e., a reduction of apparent viscosity close to the wall). The two points of view were hotly discussed by several participants but not resolved. I believe that the two viewpoints, which involve different length scales and different levels of understanding, can be reconciled.

Wilkinson (NASA) investigated a flat plate with riblets of rectangular cross section, unlike the usual V-groove riblets, and presented near-wall velocity measurements for a range of rib spacings. He found significant reductions of velocity fluctuations even at large spacings, when compared to a smooth plate, and found, on the basis of time-delay correlations of wall shear stress and velocity, that the thin element arrays of optimum spacing were directly interfering with the coherent turbulence structures at wavelengths equal to multiples of rib spacing.

Compliant Coatings

Gaster (Cambridge University) gave the first technical presentation of the symposium. In an invited paper, he reviewed the mainly favorable historical evidence for delay of transition in water with compliant coatings. He discussed the numerical problems of computing hydrodynamic stability loops by coating-induced instability waves (in addition to T-S waves), as coating softness and speed are increased. Numerical computations carried out jointly with Carpenter (Essex University), who also presented a paper at the symposium describing his contribution, indicated that compliant surfaces could be designed to reduce instability growth rates to one-third of rigid flat plate values, for a specified narrow window of flow velocities. Although the computational model assumed an idealized nondissipative coating with rigid backing plate, and the coating physical properties were not fully known, towing tank experiments described by Gaster were claimed to show good qualitative agreement with Carpenter's predictions. Gaster's optimistic forecast of practical compliant coatings for delaying transition and reducing drag in the future is certainly not shared by me. There is just too much evidence to the contrary.

In a paper on two-dimensional stationary and moving, small-amplitude wavy walls, Sengupta et al. (NAL) discussed numerical computations of friction drag in fully developed turbulent flow. The computations assumed zero pressure gradient. The frictional drag, relative to a flat plate, was found to either increase or sharply decrease (as much as 9 percent) depending on the wavy wall phase speeds and wave numbers. Pressure drag effects due to flow separation, not discussed by the authors, could easily negate any friction drag reductions.

Local Surface Heating

In addition to the paper by Corke, discussed previously, Robey (CALTECH) presented results for an array of heating elements designed to introduce 2-D and single oblique instability waves in a laminar boundary layer. He confirmed other work that shows that oblique waves can be more unstable than 2-D T-S waves, contrary to what many people have assumed since the paper of Squire (1933). However, because he did not investigate pairs of oblique waves, Robey did not identify the most unstable modes as presented by Corke.

Finally, Ryzhov (U.S.S.R. Academy of Sciences Computing Center) discussed an asymptotic theory of the interaction of a boundary layer and external potential flow in the limit as Reynolds number approaches infinity. For a local wall temperature source, the temperature field was independently determined. Ryzhov concluded, by correlation with available experimental data, that his theory for predicting the effects of heating on T-S waves was qualitatively correct and could be used as a guide for transition control.

Polymer Additions

In the symposium's only paper on polymer drag reduction, Bewersdorff and Singh (University of Dortmund) presented data on solutions of xanthum gum, a high molecular weight polysaccharide with a rigid helical structure. The gum was found to be effective in relaminarization of onset turbulence in pipe flow.

Airfoil Flow Control Problems

Pfenninger (NASA contractor), continuing his 45-year pursuit, described the detailed design of supercritical airfoils with partial boundary layer suction and concluded that full laminarization was feasible on swept wings of the X63T18 type. Kohama (Tohoku University, Sendai, Japan) presented experimental data on the leading edge flow over a supercritical NASA 998A laminar flow control wing profile that has concave-convex curvature when yaw angle is applied. He showed smoke visualization and hot-wire data on the complicated 3-D instabilities resulting from Taylor-Görtler and secondary crossflow vortices that must be controlled if laminar flow is to be maintained.

Shih and Ho (University of Southern California) presented data on airfoil unsteady flow separation in accelerating and decelerating motion. Properly phased actuation of a flap just downstream of the separation bubble successfully controlled the free shear layer and removed vortices of the same length scale as the flap chord.

Acoustic Control of Flow Separation

Sigurdson and Roshko (CALTECH) found that sound waves communicated to the flow just downstream of the separation line on a flat-faced circular cylinder aligned coaxially with the free stream could significantly reduce the size of the leading edge separation region when forcing was done at sound frequencies less than free shear layer vortex frequencies and wavelengths on the order of separation bubble height. While the general phenomenon is not new, new insights may result from the shear layer data.

Other Boundary Layer Topics

Two papers addressed the laboratory problem of simulating high Reynolds number boundary layers. Arakeri and Coles (CALTECH) reported on the successful use of vibrating pins to create an artificial turbulent boundary layer with the mean properties of a natural boundary layer, except that the large eddies are produced in an ordered fashion to facilitate understanding of the flow structure. Future work will include analysis of large-scale vorticity, wall shear, and bursting properties.

On an entirely different note, Munakata (Nikon University, Japan) presented data showing how an equilibrium boundary layer could be created on a flat plate under laboratory conditions, using transverse surface grooves. This type of manipulator could be useful, for example, in evaluating LEBU performance under field conditions.

Miksad et al. (University of Texas, Austin) described how hot-wire data taken at two points in space can be analyzed using linear and nonlinear transfer functions to chart the evolution of flow transition. Flat plate wake measurements were presented to illustrate the method.

Sreenivasan (Yale University) proposed an idealization of large-scale boundary layer turbulence in which a 2-D vortex and its mirror image in the wall provide an inviscid model of instability and formation of hairpin vortices and streak structure. Much more work will be required to sort out this approach and determine its usefulness.

JETS

Seven papers were pres[illegible] the symposium on jet flows [illegible] more fundamental papers [illegible] been discussed. Three [illegible] papers dealt with [illegible] methods to charge [illegible] mixing in jets and [illegible] were more [illegible] mentals of [illegible]

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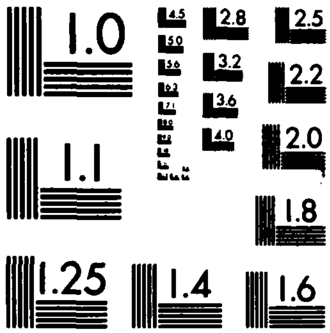

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

In the first group of three papers, Narayanan (IISc) and Platzer (U.S. Naval Postgraduate School) reported that out-of-phase periodic translation of movable lips attached to a wedge nozzle for a plane jet could lead to a tremendous increase in the rate of entrainment of fluid surrounding the jet. Detailed measurements and flow visualization showed that this resulted from formation of large vortices on either side of the jet that grew rapidly with the flow. Srinivas et al. (IISc) reported attempts to increase jet turbulence levels by fluidically controlled oscillation of jet flow rate. To produce the opposite effect, Breidenthal (University of Washington) showed that when jet velocity is linearly or quadratically accelerated, mixing can be inhibited.

Hakkinan et al. (McDonnell Douglas Research Laboratories) summarized their recent published efforts on jet and shear flow control ; these results will not be repeated here. The final paper of the symposium, by Petersen and Samat (University of Arizona), concerned acoustic excitation of azimuthal modes in a laminar axisymmetric jet. Not surprisingly, they found that the mode of jet instability of largest scale was the most amplified local shear layer instability at the end of the potential core region prior to transition from laminar to turbulent flow. Linear stability theory was successful in predicting radial distributions of velocity amplitude for very high amplitudes of excitation.

CONCLUDING REMARKS

In summary, the symposium was successful in bringing together people, primarily Americans and Indians, who are conducting research on turbulence management. It clearly showed that progress is being made. A large number of very fine papers were presented, giving new results, with convincing successes concerning understanding of the mechanics and control of transitional and turbulent flow regimes. Two-dimensional instability problems have been largely solved and the emerging focus is on the much more complex 3-D problems. It was clear at the symposium that a wide variety of insights and research courses exist, but that improved knowledge of coherent flow structures, particularly vortex structures, is a key to ultimate management of turbulent flow processes. In the future it is important to this reviewer that research at high Reynolds numbers be introduced in order to determine whether findings under laboratory conditions are valid under field conditions.

PRESENT AND FUTURE RESEARCH ACTIVITIES ON CONTROLLED NUCLEAR FUSION IN JAPAN

Osamu Ishihara

This article discusses the major research activities on controlled nuclear fusion in Japan. The largest Japanese tokamak, JT-60, is discussed along with the WT-3, a modest-size tokamak. Helical systems, such as heliotrons, are also discussed as a method of magnetic confinement. As for inertial confinement fusion, laser fusion research at Osaka University is reviewed.

INTRODUCTION

I was pleased to have the opportunity to attend the 11th International Conference on Plasma Physics and Controlled Nuclear Fusion Research held in Kyoto from 13 to 20 November 1986. This was the second international conference on plasma physics held in Japan in recent years. The first conference, which was held in 1980, focused on basic plasma physics.* The second conference focused on the major research activities on controlled nuclear fusion rather than basic plasma physics. This conference and the tour organized during the conference to Osaka University and Kyoto University gave me the opportunity to review some of the present and future research activities on plasma physics and controlled nuclear fusion in Japan.

About 650 attendees from more than 30 countries listened to presentations on international research activities on controlled nuclear fusion. Some of the highlights of the conference include:

- The most recent experimental results of JT-60, the largest tokamak in Japan and one of the three major tokamaks in the world, were presented. The latest experiment was started just 3 months before the conference began.
- Chiyoe Yamanaka, of the Institute of Laser Engineering, Osaka University, presented the results of the GEKKO XII green beam D-T experiment, which attracted the attention of the Japanese newspapers because of the achievement of the largest neutron yield to date.
- Japanese plans for major magnetic confinement nuclear fusion research on helical systems and on the next generation of tokamaks were revealed.

This brief article summarizes my observations of the fusion research activities in Japan.

TOKAMAKS

JT-60

As scheduled, JT-60 resumed operation in August 1986. JT-60 had started operation in April 1985 but was shut down in July 1985 to install auxiliary heating systems. Recent

*Fisher, L.H. 1980. International conference on plasma physics 1980, Nagoya, Japan. *Scientific Bulletin* 5, no. 2:46-62.

experiments on JT-60 were summarized in the opening session of the conference by M. Yoshikawa and later in more detail by M. Nagami of the Japan Atomic Energy Research Institute (JAERI) (see the Appendix for complete addresses).

JT-60 is one of the world's three major tokamaks (break-even scale magnetic confinement fusion devices) in operation. As noted by its name, the JAERI tokamak is characterized by its toroidal vacuum chamber volume of $V \simeq 60\ m^3$, where the major radius $R = 3$ meters, minor radius $a = 0.95$ meter, and $V \simeq 2\pi R \times \pi a^2$. It was exciting to witness the announcement of the results from the most recent experiment on this giant machine, which was carried out in a wide range of plasma densities, from $n = 0.1 \times 10^{19}$ to $9.7 \times 10^{19}\ m^{-3}$, including energy confinement times of 0.5 second for Joule-heated plasma at high plasma densities and 0.12 second for neutral-beam-heated plasma at high heating power. These results are as good as the results from the other two large tokamaks in operation in the world. However, it was obvious to me that JT-60 did not achieve the H-mode in its operation yet, which the Tokamak Fusion Test Reactor (TFTR) in the United States and the Joint European Torus (JET) in England have achieved in their experiments; the formation of the H-mode is now believed to be a key to reaching the break-even stage by the tokamaks. The TFTR experimental group at the Princeton Plasma Physics Laboratory achieved transition from the L-mode (low-mode) to the H-mode (high-mode). This is considered to guarantee a new high-confinement regime, different from the L-mode regime where energy confinement time deteriorates as auxiliary heating power is increased, resulting in a world record ion temperature of 20 keV and a Lawson confinement parameter of $n\tau = 1.5 \times 10^{20}\ m^{-3} \cdot s$. The JET team, on the other hand, revealed experimental results of an energy confinement time of more than 0.8 second with $n = 4.2 \times 10^{19}\ m^{-3}$ and an ion temperature of 3 keV with ohmic heating alone. It should be emphasized, however, that the JT-60 experiment showed a synergetic effect of lower hybrid current drive and neutral beam heating to enhance current drive and heating efficiency. This effect may give a clue to overcoming the potential difficulty of operating a tokamak as a reactor, since tokamak reactors cannot operate in a steady-state manner because of their transformer action.

WT-3

At Kyoto University, research on a new, modest-size tokamak is being conducted by Professors S. Tanaka and R. Itatani. WT-3 is apparently the successor of WT-2, which was used effectively to study wave propagation in a toroidal device. A few years ago Professor Tanaka accepted an award for his outstanding research achievement in the Plasma Physics Division of the American Physical Society. That citation referred to his contribution to tokamak research in the lower hybrid current drive experiment. WT-3, which is used to conduct research on RF heating and current drive, is now located in a new building on the crowded campus of Kyoto University and started operation in June 1986. Experiments on WT-3 (major radius/minor radius = 0.65 meter/0.22 meter), together with its predecessor WT-2, have indicated an efficient method of RF current drive by enhancing lower hybrid current drive efficiency accompanied by electron-cyclotron heating. The WT-3 experiment, a result of mutual efforts between the Faculty of Science (Physics) and the Faculty of Engineering (Engineering

Science, Electronics, Nuclear Engineering), is producing vital information of basic plasma physics for controlled nuclear fusion research. Large tokamaks like JT-60 are not suitable for studying plasma waves that may affect the performance of tokamak operation.

LASER FUSION

GEKKO XII and LEKKO VIII

Inertial confinement fusion (ICF) research at Osaka University is directed by C. Yamanaka. The GEKKO XII glass laser at Osaka University was completed in 1982. Twelve beams operate at a peak power of 55 TW with an output energy of 30 kJ, and Yamanaka reported a neutron yield of 9.4×10^{12} (each neutron from a D-T fusion reaction) from the compression of a Cannonball target with green beams. Such an achievement may be considered as comparable as the result obtained by the world's largest 100-TW/100-kJ Nova laser at the Lawrence Livermore National Laboratory in the United States. (The Nova experiment produced a fusion product of $n\tau = 3 \times 10^{20}$ $m^{-3} \cdot s$ with an ion temperature of 1.5 keV, although much of the work on the Nova experiment is classified and was not discussed at the conference.) GEKKO XII seems to be overcoming the difficulty glass lasers had encountered in the past, that energy deposition of infrared emission is poor on a target. GEKKO XII uses the technology of higher harmonics generation, which can convert the infrared emission (a wavelength of 1.05 μm) to shorter wavelengths of 0.53 μm (optically green light) or even 0.35 μm (towards blue) and 0.26 μm. From the short-wavelength GEKKO laser experiments, a new implosion scheme was developed and a high neutron yield was achieved. Yamanaka reported further that the simulation of the new implosion scheme showed the possible ignition of D-T fuel at a laser energy larger than 100 kJ with a wavelength of 0.35 μm. It was certainly impressive when Yamanaka talked about the plans for the 100-kJ energy driver KONGOH achieving the scientific break-even condition in the 1990s.

In addition to studying glass lasers, Osaka University is also doing research on carbon dioxide (CO_2) laser drivers. As a new approach to nuclear fusion, a hybrid fusion scheme, magnetically insulated inertially confined fusion (MICF), was reported by S. Nakai. MICF was demonstrated to be feasible by the CO_2 laser LEKKO VIII, which is rated at 10 TW/10 kJ, with a focused beam of 300 Joules in 1 ns. Although there is no official announcement yet, Dr. Nakai is likely to succeed Dr. Yamanaka after his retirement in March 1987.

OTHER NOTEWORTHY EFFORTS

It is remarkable to note the development and diversity of the Japanese controlled nuclear fusion efforts, which are stimulated by the need for more energy because Japan lacks natural energy resources. The following are a few examples of other noteworthy efforts on controlled nuclear fusion research.

Heliotrons

A heliotron is a device to confine plasma in a toroidal vacuum chamber with helical magnetic field coils. The Heliotron E, which has a major radius of R = 2.2 meters and a minor radius of a = 0.21 to 0.4 meter, is located at the Uji campus of Kyoto University. *Professor Uo has been advocating the* advantages of heliotron reactors over tokamak reactors because of the heliotron's currentless operation. The Heliotron E uses microwave power supplied by a 53-GHz gyrotron to produce and maintain steady-state plasma. The neutral beam injection (NBI) experiment produced a Lawson value of $n\tau = 5 \times 10^{18}\ m^{-3} \cdot s$ with an energy confinement time of $\tau \approx 0.02$ second, which may be considered to be a better result compared with the modest-size tokamak experiments. The probable shortcoming of the heliotron, however, is the large aspect ratio (i.e., $R/a \approx 10$, while tokamaks have an aspect ratio of $R/a \approx 3$), which necessarily makes the vacuum chamber huge. In fact, the building that houses the Heliotron E at the Uji campus is much larger than those housing tokamaks with comparable plasma size. In the United States, a stellarator (advanced toroidal facility (ATF), a helical system similar to the heliotron) will start operation in the spring of 1987 at the Oak Ridge National Laboratory after a long tokamak-dominated period. Encouraged by this news, Professor Uo is excited about pursuing the realization of a heliotron reactor (Heliotron H) with a major radius of 21 meters and a minor radius of 1.8 meters. He may encounter technical difficulties in constructing such a huge device; future tokamak reactors in discussion at the conference, the International Tokamak Reactor (INTOR) and the Next European Torus (NET), are less than 6 meters in major radius. The heliotron group headed by Uo is now planning to build a break-even device, the Heliotron F.

Tandem Mirror GAMMA 10

One major experiment of an open magnetic confinement system in Japan is the tandem mirror GAMMA 10 directed by S. Miyoshi at the University of Tsukuba. Y. Kiwamoto in the Plasma Research Center reported an axial confinement time of $\tau_{\parallel} = 0.4$ second with a central cell density of $n_C = 3 \times 10^{18}\ m^{-3}$. GAMMA 10 is the only major mirror fusion experiment in the world since the United States terminated the Mirror Fusion Test Facility B program at Livermore.

REPUTE 1

REPUTE 1 (Reversed Field Pinch, University of Tokyo Experiment) is a toroidal device with a major radius of $R = 0.82$ meter and a minor radius of $a = 0.2$ meter and is directed by K. Miyamoto. Different from tokamaks, the toroidal magnetic field in the REPUTE 1 reversed in direction in the outer region of the plasma column. The reversed field pinch configuration the REPUTE 1 produces has been suggested as an alternative system to controlled nuclear fusion.

Institute of Plasma Physics

H. Ikegami, of the Institute of Plasma Physics, Nagoya University, reported the final results of the Nagoya Bumpy Torus experiment at the conference. The experiment was designed to confine charged particles in bumpy toroidal magnetic fields. Nagoya nuclear-fusion-related experiments will be rearranged after the 25th anniversary of the Institute of Plasma Physics (the ceremony is planned right after the conference). A major experiment at Nagoya will focus not on tokamaks but on helical devices under the directorship of T. Uchida.

Institute for Fusion Theory

The Theory group at Hiroshima University continues to contribute to the theoretical background of controlled nuclear fusion. The group is directed by Professor Nishikawa.

ETIGO Project

At the Technological University of Nagaoka, an inertial confinement fusion research program using an intense pulsed light-ion beam as a driver has been conducted. The program is called ETIGO (an old name for the prefecture of Niigata) and is headed by K. Yatsui.

Osamu Ishihara is an Associate Professor in the Department of Electrical Engineering at Texas Tech University in Lubbock, Texas. He received his undergraduate degree from Yokohama National University and his Ph.D. from the University of Tennessee. Dr. Ishihara previously spent 7 years at the University of Saskatchewan in Saskatoon, Canada. He is a member of the American Physical Society and the IEEE Nuclear and Plasma Sciences Society. Dr. Ishihara's current research interests include plasma waves, instabilities, turbulence, nuclear fusion research, astroplasma physics, and space plasmas.

Appendix

ADDRESSES OF CONTACTS

M. Yoshikawa and M. Nagami
Naka Fusion Research Establishment
Japan Atomic Energy Research Institute
Naka-machi, Naka-gun
Ibaraki-ken 311-02 Japan

S. Tanaka
Department of Physics
Faculty of Science
Kyoto University
Kitashirakawa, Sakyo-ku
Kyoto 606 Japan

R. Itatani
Department of Electronics
Faculty of Engineering
Kyoto University
Kitashirakawa, Sakyo-ku
Kyoto 606 Japan

Chiyoe Yamanaka
Institute of Laser Engineering
Osaka University
Yamada-oka 2-6, Suita
Osaka 565 Japan

S. Nakai
Institute of Laser Engineering
Osaka University
Yamada-oka 2-6, Suita
Osaka 565 Japan

Koji Uo
Plasma Physics Laboratory
Kyoto University
Gokasho, Uji,
Kyoto 611 Japan

S. Miyoshi
Plasma Research Center
University of Tsukuba
Sakuramura Niihari-gun
Ibaraki-ken 305 Japan

Kenro Miyamoto
Department of Physics
Faculty of Science
University of Tokyo
7-3-1 Hongo, Bunkyo-ku
Tokyo 113 Japan

T. Uchida
Institute of Plasma Physics
Nagoya University
Furo-cho, Chikusa-ku
Nagoya 464 Japan

Kyoji Nishikawa
Institute for Fusion Theory
Hiroshima University
1-1-89 Higashi-Sendacho Naka-ku
Hiroshima 730 Japan

K. Yatsui
Laboratory of Beam Technology
Technological University of Nagaoka
Nagaoka
Niigata 940-21 Japan

SUPERCONDUCTIVE ELECTRONICS IN CHINA

T. Van Duzer

Although China has more professionals engaged in superconductive electronics research than the U.S. or Japan, it lags behind other countries because of equipment and infrastructure deficiencies. The research that is being conducted is high quality and is directed to SQUID magnetometry for biological and geophysical applications and to millimeter and submillimeter wave applications.

EDITOR'S NOTE

Dr. T. Van Duzer, from the University of California at Berkeley, attended the International Conference on Semiconductor and Integrated Circuit Technology in Beijing, People's Republic of China, from 19–26 October 1986. While in China he also presented lectures and held technical discussions at four universities/institutes. This article summarizes the information he obtained during the conference and at the universities/institutes he visited.

SUMMARY OF RESEARCH ON SUPERCONDUCTIVE ELECTRONICS IN CHINA

There are 15 groups in mainland China that are working on electronics applications of superconductors. It was estimated by a leader of one of the groups that there are about 200 professional-level researchers including faculty, full-time research staff, and graduate students, but not including the undergraduates who do B.S. degree projects. This number exceeds those for the U.S. or Japan, but the efficiency in China is lower because of equipment and infrastructure deficiencies and because travel budgets limit access to the main information flow in Japan and in the West.

Most of the research is directed to superconducting quantum interference device (SQUID) magnetometry for biological and geophysical applications and to millimeter and submillimeter wave applications. They are necessarily expending effort on fabrication technology. Several groups are trying to make all-refractory tunnel junctions, mostly with niobium electrodes and amorphous silicon and aluminum oxide barriers. No work on integrated circuits of any significant complexity appears to be in progress, although some of the laboratories are sufficiently well equipped.

For the most part, the work is an attempt to catch up with developments abroad and to apply the technology to practical problems. The work is apparently of high quality but mostly subthreshold in the sense of not being able to push ahead of groups in other countries.

Most of the fabrication apparatus and apparently all of the test equipment is made in China, but we saw two Japanese scanning electron microscopes (SEMs) and a few vacuum systems from Japan and Europe. Their equipment (with occasional exceptions) appears to be 10 years or more behind that found in universities of comparable stature in the U.S. The reason for using Chinese sources is a lack of hard currency.

Comments indicated that superconductive electronics is not a high-priority item for China; research funds are scarce and support for study abroad is difficult to obtain.

We saw the library at one school; it was well stocked with copies of Western journals. It is apparently the practice to photo-offset copy the journals for distribution in China.

RESEARCH GROUPS IN SUPERCONDUCTIVE ELECTRONICS

Beijing

- Beijing University (joint effort of Computer Science and Physics Departments)
    * Junction materials studies
- Institute of Physics, Academy of Science
    * Refractory metal junctions
    * dc SQUIDs
- National Institute of Metrology
    * RF SQUIDs
    * Voltage standard
    * Current comparator

Chang Chun (Northeast China)

- Institute of Geology
    * dc SQUIDs

Xian

- Northwestern University (Department of Physics)
    * Mixer noise

Chengdu

- Chengdu Institute of Telecommunications
    * Josephson mixer
- National Institute of Metrology (southwest branch)
    * Voltage standard

Hefei

- Hefei Research Institute of Cryogenics and Electronics
    * Moving to Hefei from Chengdu has caused a major hiatus (perhaps 2 years) in work on parametric amplifiers (probably x-band)
- University of Science and Technology
    * Fluxon oscillator
    * Cavities

Nanjing

- Nanjing University (Information Physics Department)
    * Detection and mixing at millimeter and submillimeter wavelengths
    * Vortex propagation in long junctions
    * Phonon generation and detection

Shanghai

- Fudan University
    * RF SQUIDs
- Tongji University
    * SQUIDs
- Shanghai Institute of Science and Technology
    * New laboratory
    * Possibly mixing interest

- Shanghai Jiaotong University (Department of Electronic Engineering)

  * Superconducting FET
  * All-refractory junctions

I visited the research laboratories at Beijing University, Academy of Science Institute of Physics, Nanjing University, and Jiaotong University.

Beijing University

The work here is a collaborative effort of the Computer Technology and Physics Departments. Professor Xiuwen Wu is in charge of the Microelectronics Laboratory. A large clean building for fabrication has just been built, but it is empty at present. Currently fabrication is being done in the Physics Department by Professor Xiaofan Meng, a colleague, Professor Qui Li, and several graduate students. They are working on refractory materials for tunnel junctions. They reported a tunnel junction with Nb_3Sn base electrode and lead counter electrode at the conference. They have an excellent new Balzer high-vacuum sputtering system and a new Hitachi SEM that they will adapt for one-level e-beam lithography. The group is small but the work is of high quality.

Academy of Science Institute of Physics

This institute has about 30 researchers. There is a group of 20 working under Lin Li ("Anna L. Lee") on new materials including magnet materials, phonon spectra, nonequilibrium effects by tunneling injection, and new high-T_C materials. A group of 10 (including 2 technicians) works under Peiran Yang on tunneling effects. The equipment for this group includes a high-vacuum Balzer e-beam deposition system equipped with an ion mill and an Auger analysis system. They also have an ion mill, plasma etcher, and several simple vacuum systems. They have tried to make Nb-αSi-Nb and Nb-AlO_x-Nb junctions without yet having good results. The group has made a dc SQUID magnetometer using Nb-NbO_x-PbIn tunnel junctions and has achieved noise floors slightly higher than commercial systems in the U.S. (about 10 times higher than the best laboratory results).

Nanjing University

The superconductive electronics work is in the Information Physics Department and is led by Professor Pei Hang Wu. He is aided by Assistant Professors Qui-Heng Chang and Shen-Zu Yong. There are eight full-time professional research assistants and eight graduate students. Most of the work of the group has been in millimeter and submillimeter wave detection and mixing. They stopped using point contacts in 1984 and have used 1-μm^2 Pb alloy junctions since then. The lithography is by the suspended resist (Dolan) method. Measurements have been made at 3 cm and 8 mm. They use Gunn oscillators (made in China) for the signal and local oscillator at 8 mm. They got mixer gain of 0.6 and T_m = 100 K at 36 GHz. These measurements were made in a shielded room. They are putting together a system using a CO_2 pumped laser that gives about 20 lines from 500 to 80 μm. The dewar for the submillimeter wave measurements is part of a closed-cycle system (Air Products). The group is also working on electronic analogs including one to simulate SIS junctions. They have done computer studies of long junctions and are working toward experimental studies of fluxon oscillators. In another project they are studying phonon generation and detection.

Shanghai Jiaotong University

Professor Jei Fei Jiang and Associate Professor Chun Xi Guo of the Department of Electronic Engineering (formerly Applied Physics) are involved in research to make Nb–αSi–Nb junctions in a small Anelva system. The experimental work is being done in the laboratory of Professor Yi Xin Chen. He has a dry etcher, a contact printer, and a computer-controlled SEM for e-beam lithography. In addition to Jiang and Guo, the superconductivity group includes three teachers, who also do research, and two M.S. students. They are working on circuit-simulation programs and are also doing experimental work to make superconductor semiconductor superconductor coplanar junctions. This group is quite new and is presently trying to set the direction of their research. They plan to do work in the new research laboratory of VLSI Electronics, which has a clean new fabrication room.

Theodore Van Duzer is a professor of electrical engineering and computer science at the University of California at Berkeley. He received a B.S. degree in 1954 from Rutgers University, an M.S. degree in 1957 from the University of California at Los Angeles, and a Ph.D. degree in 1960 from the University of California at Berkeley. Dr. Van Duzer has served as visiting professor at the Technical University, Vienna; the Catholic University of Chile; Rutgers University; Kyoto University, Japan; the University of Paris; and the Aristotelian University of Thessaloniki. He is a member of Eta Kappa Nu, Tau Beta Pi, and Sigma Xi and is a Fellow of IEEE. Dr. Van Duzer's current research interests include electromagnetic theory, solid-state devices, and superconductivity.

INTERNATIONAL MEETINGS IN THE FAR EAST

1987-1993

Compiled by Yuko Ushino

The Australian Academy of Science, the Japan Convention Bureau, and the Science Council of Japan are the primary sources for this list. Readers are asked to notify us of any upcoming international meetings and exhibitions in the Far East which have not yet been included in this report.

1987

Date	Title, Attendance	Site	For information, contact
April 8-11	International Symposium on Physics of Magnetic Materials (ISPMM'87) 18-F50-J150*	Sendai, Japan	Department of Applied Physics, Faculty of Engineering, Tohoku University Aoba, Aramaki, Sendai 980
April 14-16	The 20th JAIF Annual Conference (JAIF-Japan Atomic Industrial Forum) 27-F200-J1,000	Tokyo, Japan	Japan Atomic Industrial Forum, Inc. Toshin Building, 1-1-13 Shimbashi, Minato-ku, Tokyo, 105
April 14-17	The 25th International Magnetics Conference (INTERMAG'87) 32-F500-J1,000	Tokyo, Japan	The Magnetics Society of Japan Kotohira Kaikan Building, 1-2-8 Toranomon, Minato-ku, Tokyo 105
April 15-18	The 1st Yukawa International Seminar "Mesons and Quarks in Nuclei"	Kyoto, Japan	YKIS '87, Research Institute for Fundamental Physics, Kyoto University Oiwake-cho, Kitashirakawa, Sakyo-ku, Kyoto 606
April 20-22	International Symposium on Magnetism of Intermetallic Compounds 20-F80-J150	Kyoto, Japan	Department of Metal Science and Technology, Faculty of Engineering, Kyoto University Yoshida-Honmachi, Sakyo-ku, Kyoto 606
April 20-22	International Symposium on Magneto-Optics 16-F50-J150	Kyoto, Japan	NHK Science and Technical Research Laboratories 1-10-11 Kinuta, Setagaya-ku, Tokyo 157

*Note: Data format was taken from the Japan International Congress Calendar published by the Japan Convention Bureau.

No. of participating countries
F: No. of overseas participants
J: No. of Japanese participants

1987

Date	Title, Attendance	Site	For information, contact
April 20-22	Toyohashi International Conference on Ultrasonic Technology 20-F100-J300	Toyohashi, Japan	Michiko Takamori, MYU Research 2-32-3-303 Sendagi, Bunkyo-ku, Tokyo 113
April 20-24	The 11th Particles and Nuclei International Conference (PANIC'87) 40-F450-J450	Tokyo, Japan	Professor Koji Nakai, National Laboratory for High Energy Physics 1-1 Uehara, Oho-machi, Tsukuba-gun, Ibaraki 305
April (tentative)	Very Large Systems Integration Conference	Melbourne, Australia	Conference Manager, The Institution of Engineers, Australia 11 National Circuit, Barton, ACT 2600
April 30-May 1	Australian Academy of Science--Annual General Meeting	Canbella, Australia	Secretariat: Australian Academy of Science GPO Box 783, Canberra, ACT 2601
May 10-16	The 7th International Conference on Invertebrate and Fish Tissue Culture 15-F250-J150	Shizuoka, Japan	Japan Invertebrate Tissue Culture Society c/o Laboratory of Phenogenetics, National Institute of Genetics 1-111 Yata, Mishima, Shizuoka 411
May 11-14	Japan-China Ultrasonic Waves Conference	Nanjing, People's Republic of China	T. Takagi, Institute of Industrial Science, University of Tokyo 7-22-1 Roppongi, Minato-ku, Tokyo 106
May 11-15	Annual Engineering Conference	Darwin, Australia	Conference Manager, The Institution of Engineers, Australia 11 National Circuit, Barton, ACT 2600
May 11-15	The 31st Annual Meeting of the Australian Mathematical Society	Victoria, Australia	Dr. K. L. McAvaney, Division of Computing and Mathematical, Deakin University Victoria, 3217
May 17-21	The 44th General Assembly of International Magnesium Association 15-F100-J50	Tokyo, Japan	Japan Light Metal Association, Nihombashi-Asahikaikan, 2-1-3 Nihombashi, Chuo-ku, Tokyo 103
May 17-22	World Conference on Advanced Materials for Innovations in Energy, Transportation, and Communications 40-F300-J900	Tokyo, Japan	CHEMRAWN VI Coordinating Office, The Chemical Society of Japan 1-5 Kanga-Surugadai, Chiyoda-ku, Tokyo 101

Date	Title, Attendance	Site	For information, contact
May 18-21	1987 Symposium on VLSI Technology	Karuizawa, Japan	Secretariat: Business Center for Academic Societies Japan Conference Department 2-40-14 Hongo, Bunkyo-ku, Tokyo 113
May 22-23	1987 Symposium on VLSI Circuits	Karuizawa, Japan	Secretariat: Business Center for Academic Societies Japan Conference Department Yamazaki Building, 4th Floor, 2-40-14 Hongo, Bunkyo-ku, Tokyo 113
May 24-29	The 13th International Hot Atom Chemistry Symposium 10-F50-J50	Yamanashi, Japan	Department of Chemistry, Faculty of Science, University of Tokyo 7-3-1 Hongo, Bunkyo-ku, Tokyo 113
May (tentative)	Symposium for Quantitative Aspects of the Nitrogen Cycle	Brisbane, Australia	Dr. R. J. Myers, CSIRO Division of Tropical Crops and Pastures St. Lucia, QULD 4067
June 2-5	Transducers '87 20-F200-J600	Tokyo, Japan	Secretariat: Transducer '87 c/o Sansei International Inc., Fukide No. 2 Building, 4-1-21 Toranomon, Minato-ku, Tokyo 105
June 8-12	1987 International Congress on Membranes and Membrane Processes (ICOM'87) 30-F200-J400	Tokyo, Japan	Institute of Industrial Science, University of Tokyo 7-22-1 Roppongi, Minato-ku, Tokyo 106
June 22-25	The 1st Congress of Asian Federation of Societies for Ultrasound in Medicine and Biology 20-F50-J300	Tokyo, Japan	Japan Society of Ultrasonics Medicine c/o International Conference Organizers, Inc. 2-4-6 Minamiaoyama, Minato-ku, Tokyo 107
July 6-10	The 6th International Conference on the Physics of Non-Crystalline Solids F70-J130	Kyoto, Japan	Professor F. Sakka, The Institute for Chemical Research, Kyoto University Gokanosho, Uji-City, Kyoto 611
July 13-18	The 34th International Field Emission Symposium F40-J80	Osaka, Japan	Dr. Shogo Nakamura, The Institute of Scientific and Industrial Research, Osaka University 8-1 Mihongaoka, Ibaraki-shi, Osaka 567

Date	Title, Attendance	Site	For information, contact
July 19-24	The International Conference on Heteroatom Chemistry-IUPAC 300-F100-J400	Kobe, Japan	Institute for Chemical Research, Kyoto University Gokasho, Uji, Kyoto 611
July 20-25	The Second IFSA (Italy, France, Spain, America) Congress (2nd IFSA Congress)	Tokyo, Japan	Secretariat: The Second IFSA Congress c/o The Society of Instrument and Control Engineers, 1-35-28-303 Hongo, Bunkyo-ku, Tokyo 113
July 26-31	XXV International Conference on Coordination Chemistry	Nanjing, People's Republic of China	Professor Xiao-Zeng You, Coordination Chemistry Institute Nanjing, Jansu Province
Undecided	The International Conference on Computers in Chemical Research and Education (the ICCCRE)	Shanghai, People's Republic of China	Dr. Yongzheng Hui, Shanghai Institute of Organic Chemistry, Academia Sinica 345 Lingling Lu, Shanghai 200032
August 8-10	Neutron Scattering Symposium 1987	Sydney, Australia	Professor T. M. Sabine, School of Physics and Materials, NSW Institute of Technology P.O. Box 123, Broadway, NSW 2007
August 12-20	The 14th International Congress of Crystallographers	Perth, Australia	Dr. E. N. Maslen, Centre for Crystallography, University of Western Australia WA 6009
August 17-21	1987 Luminescence International Conference	Beijing, People's Republic of China	Professor Xu Xurong, Chinese Society of Luminescence, Xinmin Street 13 Chang-chun, People's Republic of China
August 19-26	The 18th International Conference on Low Temperature Physics 38-F600-J750	Kyoto, Japan	Professor Shinji Ogawa, The Institute for Solid State Physics, Tokyo University 7-22-1 Roppongi, Minato-ku, Tokyo 106
August 24-27	The 7th International Conference On Quarks-Leptons Physics in Collision 15-F130-J80	Tsukuba, Japan	Organizing Committee: The 7th International Conference on Physics in Collision c/o National Laboratory for High Energy Physics, 1-1 Uehara, Ohomachi, Tsukuba-gun, Ibaraki 305

1987

Date	Title, Attendance	Site	For information, contact
August 25-28	IUTAM Symposium on Non-linear Water Waves	Tokyo, Japan	Professor H. Maruo, Department of Naval Architecture, Yokohama National University Tokiwa-dai, Hodogaya-ku, Yokohama 240
August 26-29	Pacific Rim Congress 87 International Congress on the Geology Structure, Mineralisation and Economics of the Pacific Rim	Gold Coast, Australia	Mr. E. Brennan, Congress Convenor, The Australasian Institute of Mining Metallurgy, Clunies Ross House, Royal Parade, Parkville, Victoria 3052
August 27-30	The 6th International Conference on Biomagnetism 20-F300-J500	Tokyo, Japan	Secretariat: The 6th International Conference on Biomagnetism c/o INTER Group, Akasaka Yamakatsu Building, 8-5-32 Akasaka, Minato-ku, Tokyo 107
August 31-September 1	Yamada Conference XVIII on Superconductivity in Highly Correlated Fermion Systems-YCS '87 F120-J80	Sendai, Japan	Secretariat: YCS '87 c/o Research Institute for Iron, Steel and Other Metals, Tohoku University 2-1-1 Katahira, Sendai 980
August 31-September 4	The 8th International Symposium on Plasma Chemistry	Tokyo, Japan	Professor Kazuo Akashi, Metallurgy, Faculty of Engineering, University of Tokyo 7-3-1 Hongo, Bunkyo-ku, Tokyo 113
August 31 September 4	IUTAM Fundamental Aspects of Vortex Motion 10-F40-J60	Tokyo, Japan	Secretariat: Department of Physics, University of Tokyo 7-3-1 Hongo, Bunkyo-ku, Tokyo 113
August (tentative)	The 10th International Congress of Pharmacology	Sydney, Australia	Professor J. Shaw, Secretary, Interium Organising Committee, Department of Pharmacology, University of Sydney NSW 2006
August (tentative)	International Congress for Pharmacology, Satellite on Cardio-Active Drugs	Hayman Island, Australia	Australian Convention and Travel Services GPO Box 1929, Canberra, ACT 2601
September 2-4	Structural Engineering Conference	Melbourne, Australia	Conference Manager, The Institution of Engineers, Australia 11 National Circuit, Barton, ACT 2600

Date	Title, Attendance	Site	For information, contact
September 6-11	The 6th Pacific Basin Conference	Beijing, People's Republic of China	Dr. Chih Wang, 3110 Chintimini Drive, Corvallis, Oregon 97330, U.S.A.
September 16-18	International Symposium on Optical Memory	Tokyo, Japan	Optoelectronic Industry and Technology Development Association 5th Floor, No. 20 Mori Building, 2-7-4 Nishi-Shimbashi, Minato-ku, Tokyo 105
September (tentative)	International Computer Graphics Symposium 4-F60-J300	Sapporo, Japan	Incorporated Foundation Sapporo Electronics Center 31 Shimonopporo, Atsubetsucho, Shiroishi-ku, Sapporo 004
September (tentative)	Submarine Technology Conference	Canberra, Australia	Conference Manager, The Institution of Engineers, Australia 11 National Circuit, Barton, ACT 2600
October 5-9	IEEE Computer Society's 11th International Computer Software and Applications Conference 20-F400-J900	Tokyo, Japan	c/o Information Processing Society of Japan 2-40-14 Hongo, Bunkyo-ku, Tokyo 113
October 6-9	IMACS/IFAC International Symposium on Modeling and Simulation of Distributed Parameter Systems 20-F50-J110	Hiroshima, Japan	Professor Tanehiro Futagami Civil Engineering, Hiroshima Institute of Technology 725 Miyake, Itsukaichi-cho Saeki-ku, Hiroshima 731-51
October 12-16	The 12th International Conference on Atomic Collisions in Solids 20-F80-J160	Okayama, Japan	Professor Fuminori Fujimoto, Physics Section, College of General Education, University of Tokyo 3-8-1 Komaba, Meguro-ku, Tokyo 153
October 12-16	Chapman Conference on Plasma Waves and Instabilities in Magnetospheres and at Comets F100-J50	Miyagi, Japan	Faculty of Science, Tohoku University Aoba, Aramaki, Sendai 980
Octrober 14-17	Tokyo Seminar on Macromolecule-Metal 10-F50-J150	Tokyo, Japan	Organizing Committee, Tokyo Seminar on Macromolecule-Metal Complexes c/o Ibaraki University Bunkyo, Mito 310

Date	Title, Attendance	Site	For information, contact
October 15-16	Microoptics Conference '87	Tokyo, Japan	Professor Kenichi Iga, Program Cochair MOC '87 Tokyo Institute of Technology 4259 Nagatsuta, Midori-ku, Yokohama 227
October 18-24	International Towing Tank Conference (ITTC) 30-F100-J100	Kobe, Japan	Society of Naval Architects of Japan (SNAJ) Sempaku-Shinko Building, 8th Floor, 1-15-16 Toranomon, Minato-ku, Tokyo 105
October 20-23	International Conference on Quality Control—1987 Tokyo 45-F350-J400	Tokyo, Japan	Union of Japanese Scientists and Engineers 5-10-11 Sendagaya, Shibuya-ku, Tokyo 151
October 26-29	The 2nd International Symposium on Transport Phenomena in Turbulent Flows 20-F100-J150	Tokyo, Japan	Department of Mechanical Engineering, University of Tokyo 7-3-1 Hongo, Bunkyo-ku, Tokyo 113
November 3-6	The 3rd International Photovoltaic Science and Engineering Conference 23-F150-J300	Tokyo, Japan	Japan Society of Applied Physics c/o Japan Convention Service, Inc. 2-2-1 Uchisaiwai-cho, Chiyoda-ku, Tokyo 100
November 4-6	'87 International Symposium on Science and Technology of Sintering	Tokyo, Japan	Professor Shigeyuki Somiya, Sintering '87, Tokyo c/o Nikkan Kogyo Shimbun, Ltd., Planning Bureau 8-10 Kudan Kita 1-chome, Chiyoda-ku, Tokyo 102
November 9-12	The 19th Yamada Conference on Ordering and Organization in Ionic Solutions 10-F40-J100	Kyoto, Japan	Department of Polymer Chemistry, Kyoto University Yoshida-hommachi, Sakyo-ku, Kyoto 600
November 9-13	The 2nd International Conference on Refractories 6-F170-J270	Tokyo, Japan	Secretariat: The 2nd International Conference on Refractories c/o International Congress Service, Inc. Kasho Building, 2-14-9 Nihombashi, Chuo-ku, Tokyo 103
November 15-18	1987 Global Telecommunications Conference (GLOBECOM'87) 30-F500-J700	Tokyo, Japan	Secretariat: GLOBECOM'87 c/o KDD Research and Development Laboratories 2-1-23 Nakameguro, Meguro-ku, Tokyo 153

1987

Date	Title, Attendance	Site	For information, contact
November 25-27	The 18th Japan Conference on Radiation and Radio-isotopes 30-F60-J600	Tokyo, Japan	Japan Atomic Industrial Forum, Inc. Toshin Building, 1-1-13 Shimbashi, Minato-ku, Tokyo 105

1988

Date	Title, Attendance	Site	For information, contact
January 28-31	Royal Australian Chemical Institute, Division of Inorganic Chemistry, National Meeting (COMO 13)	Melbourne, Australia	Dr. P. Tregloan, Department of Inorganic Chemistry, University of Melbourne Parkville, Victoria 3052
February 2-5	The International Association of the Institute of Navigation (IAIN) Congress	Sydney, Australia	The Australian Institute of Navigation Box 2250, G.P.O. Sydney, New South Wales, Australia 2001
February 22-26	Engineering Conference	Sydney, Australia	The Conference Manager, The Institution of Engineers, Australia 11 National Circuit, Barton, ACT 2600
February (tentative)	The 10th Australian Electron Microscopy Conference	(Undecided)	Secretariat: Australian Academy of Science GPO Box 783, Canberra, ACT 2601
March 14-16	International Symposium on Non-Equilibrium Solid Phase of Metals and Alloys F100-J200	Kyoto, Japan	Department of Metal Science and Technology, Faculty of Engineering, Kyoto University Yoshida-hommachi, Sakyo-ku, Kyoto 600
April 4-12	The 4th International Conference on Aluminium Association (JLWA) 32-F100-J150	Tokyo, Japan	Japan Light Metal Welding and Construction Weldment Yura Building, 3-37-23 Kanda-Sakumacho, Chiyoda-ku, Tokyo 101
April 19-23	International Conference on Nuclear Power Plant Water Chemistry-Operation Experience and Sophisticated Management Technology	(to be decided)	Japan Atomic Industrial Forum, Inc. Toshin Building, 1-1-23 Shimbashi, Minato-ku, Tokyo 105
April 26-May 3	The 3rd World Biomaterials Conference 15-F500-J500	Kyoto, Japan	Japan Society for Biomaterials c/o Institute for Medical and Dental Engineering, Tokyo Medical and Dental University 2-3-10 Kanda-Surugadai, Chiyoda-ku, Tokyo 101

1988

Date	Title, Attendance	Site	For information, contact
May 16-20	The 4th International Conference on Metalorganic Vapor Phase Epitaxy	Hakone, Japan	Professor T. Katoda, Secretary, ICMOVPE IV c/o International Congress Service, Inc. Kasho Building 2F, 2-14-9 Nihombashi Chuo-ku, Tokyo 103
June 5-10	The 6th International Conference on Surface and Colloid Science	Hakone, Japan	Division of Colloid and Surface Chemistry, The Chemical Society of Japan 1-5 Kanda-Surugadai, Chiyoda-ku, Tokyo 101
June 6-10	International Conference on Physical Metallurgy of Thermomechanical Processing of Steels and Other Metals 20-F100-J100	Tokyo, Japan	Nippon Tekko Kyokai 3rd Floor, Keidanren Kaikan, 1-9-4 Otemachi, Chiyoda-ku, Tokyo 100
July 1-12	The 16th International Congress of Photogrammetry and Remote Sensing 48-F2,000-J2,600	Kyoto, Japan	Japan Society of Photogrammetry 601 Daiichi Honan Building, 2-8-17 Minami-Ikebukuro, Toshima-ku, Tokyo 171
July 12-15	The 6th International Conference on Ultrafast Phenomena 20-F200-J200	Shiga, Japan	The 6th International Conference on Ultrafast Phenomena Organization Committee c/o OPTO Marketing Service Ltd. Maenocho Heights 5-206, 6-10 Maenocho, Itabashi-ku, Tokyo 174
July 17-23	International Congress of Endocrinology 48-F2,000-J2,600	Kyoto, Japan	Japan Endocrine Society c/o Seirenkaikan, Kyoto Furitsu Medical University, Nishizume Konjinbashi, Kamigyo-ku, Kyoto 602
July 18-22	1988 XVI International Conference on Quantum Electronics 30-F300-J700	Tokyo, Japan	Optoelectronic Industry and Technology Development Association No. 20 Mori Building, 2-74 Nishi-shimbashi, Minato-ku, Tokyo 105
July 25-30	International Conference on Clustering Aspects in Nuclear and Subnuclear Systems 31-F150-J150	Kyoto, Japan	Dr. K. Tanaka, Faculty of Science, Hokkaido University 5-chome, Kita 10-jo, Kita-ku, Sapporo 060

Date	Title, Attendance	Site	For information, contact
August 1-5	The 10th Congress of the International Ergonomics Association	Sydney, Australia	Ergonomics Society of Australia and New Zealand, Science Centre 35-43 Clarence Street, Sydney, NSW 2000
August 1-6	The IUPAC 32nd International Symposium on Macromolecules 50-F600-J1,200	Kyoto, Japan	The Society of Polymer Science, Japan 5-12-8 Ginza, Chuo-ku, Tokyo 104
August 14-19	The 10th International Congress on Rheology	Sydney, Australia	R. I. Tanner, Department of Mechanical Engineering, University of Sydney NSW 2006
August 15-17	International Federation of Automatic Control Symposium	Melbourne, Australia	Conference Manager, The Institution of Engineers, Australia 11 National Circuit, Barton, ACT 2600
August 15-17	Electrical IFAC Conference	Melbourne, Australia	Conference Manager, The Institution of Engineers, Australia 11 National Circuit, Barton, ACT 2600
August 15-19	The 3rd International Phycological Congress	Melbourne, Australia	Dr. M. N. Clayton, Botany Department, Monash University Clayton, Victoria 3168
August 16-19	The 7th International IUPAC Symposium on Mycotoxins and Phycotoxins 38-F100-J200	Tokyo, Japan	Japan Association of Mycotoxicology, Science University of Tokyo c/o Science University of Tokyo 12 Fungagawara-machi, Ichigaya, Shinjuku-ku, Tokyo 160
August 21-26	International Geographical Congress	Sydney, Australia	Secretariat: Australian Academy of Science GPO Box 783, Canberra, ACT 2601
August 22-26	The 5th Australia-New Zealand Conference on Geomechanics	Sydney, Australia	Conference Manager, The Institution of Engineers, Australia 11 National Circuit Barton, ACT 2600
August 30-September 2	The 5th International Conference on Molecular Beam Epitaxy 15-F150-J400	Hokkaido, Japan	Japan Society of Applied Physics c/o Department of Physical Electronics, Tokyo Institute of Technology 2-12-1, Oh-okayama, Meguro-ku, Tokyo 152
September 5-8	The 1st International Conference on Computational Methods in Flow Analysis F250-J300	Okayama, Japan	Okayama University of Science 1-1 Ridaicho, Okayama 700

1988

Date	Title, Attendance	Site	For information, contact
November 19-26	The 13th International Diabetes Federation Congress 20-F80-J120	Sydney, Australia	Professor J. R. Turtle, Professor of Medicine Department of Endocrinology, University of Sydney NSW 2006

1989

Date	Title, Attendance	Site	For information, contact
July 2-7	International Conference on Coordination Chemistry	Brisbane, Australia	Professor M.A. Bennett, Research School of Chemistry, ANU P.O. Box 4, Canberra, ACT 2601
August 13-18	Solar Energy Congress Tokyo 1989 40-F600-J400	Tokyo, Japan	Japanese Section of International Solar Energy Society 322 San Patio, 3-1-5 Takada-no-baba, Shinjuku-ku, Tokyo 160
October (tentative)	Specialty Electric Conference	Sydney, Australia	Conference Manager, The Institution of Engineers, Australia 11 National Circuit, Barton, ACT 2600
1989 (tentative)	International Conference Evaluation of Materials Performance in Severe Environments-Evaluation and Development of Materials in Civil and Marine Uses 20-F80-J120	Japan (undecided)	International Conference Secretariat, Conference and Editorial Department, Iron and Steel Institute of Japan 1-9-4 Otemachi, Chiyoda-ku, Tokyo 100
1989 (tentative)	International Conference on Zinc and Zinc Alloy Coated Sheet Steels 20-F50-J150	Japan (undecided)	International Conference Secretariat, Conference and Editorial Department, Iron and Steel Institute of Japan 1-9-4 Otemachi, Chiyoda-ku, Tokyo 100

1990

Date	Title, Attendance	Site	For information, contact
May 19-26	The 27th International Navigation Congress 60-F500-J500	Japan (undecided)	Japan Organizing Committee for 27th International Navigation Congress 2-8-24 Chikko, Minato-ku, Osaka 552

1990

Date	Title, Attendance	Site	For information, contact
July (tentative)	The 10th International Congress of Nephrology 10-F1,000-J4,000	Osaka, Japan	Japanese Society of Nephrology c/o 2nd Department of Internal Medicine, School of Medicine, Tokyo 173
August 21-29	International Congress of Mathematicians	Kyoto, Japan	Research for Mathematical Sciences, Kyoto University Kitashirakawa Oiwake-cho, Sakyo-ku, Kyoto 606
September (tentative)	The 15th International Congress on Microbiology 57-F2,500-J2,500	Osaka, Japan	Preliminary Committee of International Congress of Microbiology c/o JTB Creative Inc., Daiko Building, 3-2-14 Umeda, Kita-ku, Osaka 530
1990 (tentative)	The 6th International Conference on the Science and Technology of Iron and Steel 50-F300-J500	Japan (undecided)	International Conference Secretariat and Editorial Department, Iron and Steel Institute of Japan 3F, Keidanren Kaikan, 1-9-4 Otemachi, Chiyoda-ku, Tokyo 100
1990 (tentative)	Chemeca 1990 Applied Thermodynamics	New Zealand	Conference Manager, The Institution of Engineers, Australia 11 National Circuit, Barton, ACT 2600

1991

Date	Title, Attendance	Site	For information, contact
August (tentative)	The 16th International Conference on Medical and Biological Engineering 45-F600-J900	Kyoto, Japan	ME Division, Kawasaki Medical School 577 Matsushima, Kurashiki City Okayama 701-01
August (tentative)	International Congress on Medical Physics 45-F600-J900	Kyoto, Japan	National Institute of Radiological Science 4-9-1 Anagawa, Chiba 260

1992

1993

Date	Title, Attendance	Site	For information, contact
1993 (tentative)	International Federation of Automatic Control Congress	Sydney, Australia	Conference Manager, The Institution of Engineers, Australia 11 National Circuit, Barton, ACT 2600

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